LARP

BNL - FNAL - LBNL - SLAC

LARP BEAM INSTRUMENTATION

A. Ratti

LBNL

Presented at the LARPAC meeting

Brookhaven

May 10-12, 2006

Outline

- Overview of existing instruments
  - Schottky Monitor (lead by FNAL)
  - Tune Feedback (lead by BNL)
  - Luminosity Monitor (lead by LBNL)
- Common instrumentation issues
  - Data Acquisition
- Documentation and integration at CERN

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Highligths

From Steve’s highlights:

Simultaneous tune and coupling feedback was demonstrated in RHIC - a world first

US colliders are an essential part of the LARP contribution to the LHC

Developing all instruments with experimental support of colliding beam operations

Documentation, integration issues are becoming more urgent and being addressed with a systematic approach both within the LARP and the CERN (EDMS) frameworks

Year by year funding needs to be managed closely

Introduction

Three instruments at different levels of maturity

- Schottky monitors will be mostly completed by the end of FY06
- Luminosity monitors will be under production through 06 and into 07
- Tune and coupling feedback are still under development and will reach a final design in early FY07

All three devices are on schedule to support LHC commissioning

The data acquisition platform is defined by CERN and therefore common to all LARP instruments - Held a successful workshop on April 25, 2006

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Schottky Monitors

Advanced enabling technology for:

- Non invasive tune measurement for each ring
- Non invasive chromaticity measurements
- Measure momentum spread
- Continuous online emittance monitor
- Measure beam-beam tune shift

Build in capability to monitor gain variation with time
Measure individual or multiple bunches

Technical Approach

Center frequency of 4.8 GHz

3dB BW - 300 MHZ

Sufficient for 25ns bunch spacing

Small longitudinal Z/n

No absorbers allowed

Below frequency of Schottky band overlap

Allows for adequate physical aperture

Matched pairs of SiO_2 Coax cables

Slotted Waveguide Pickup

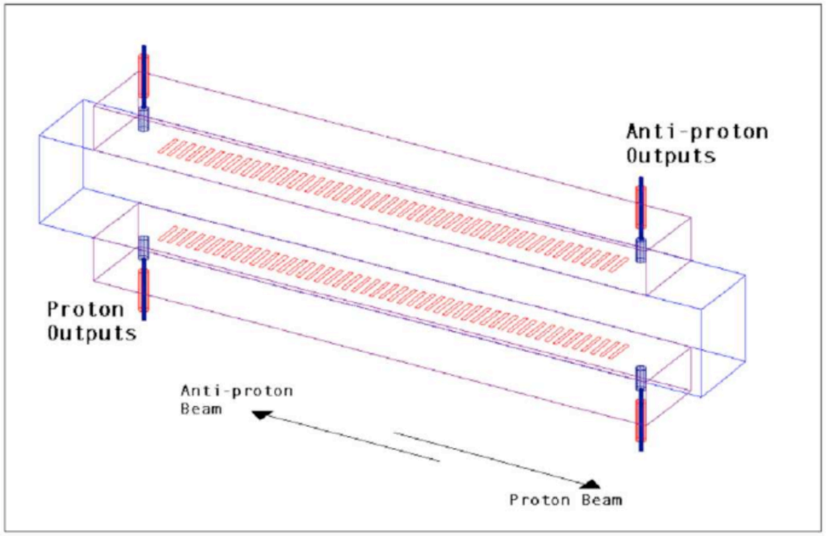
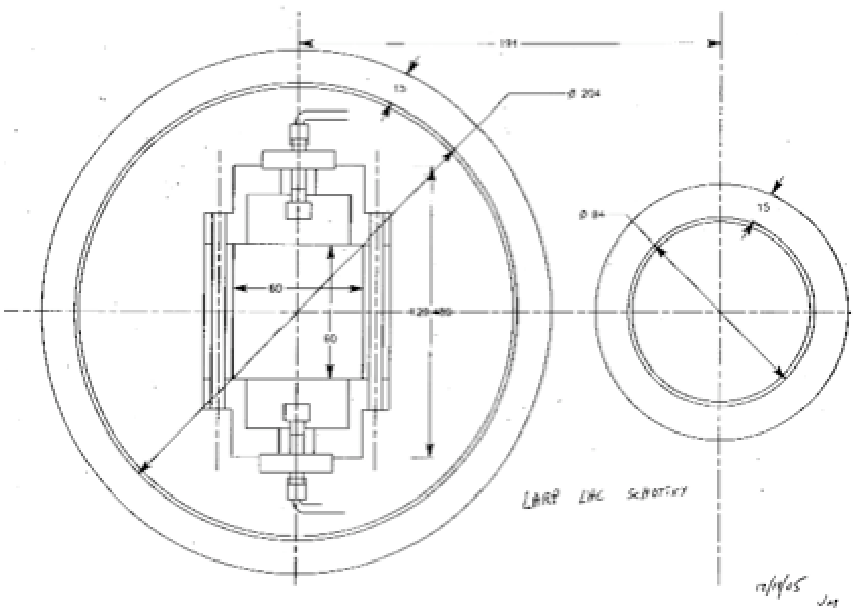
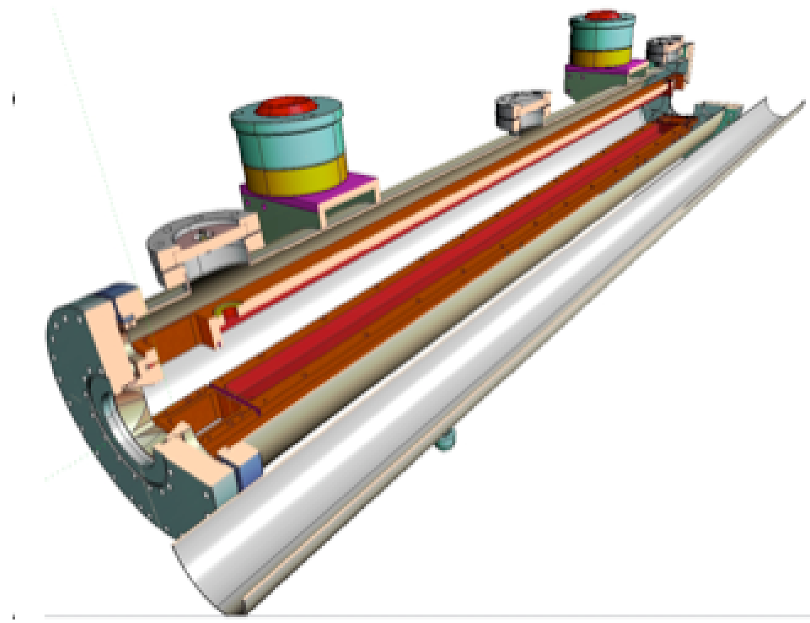


Table 1. Parameters of LHC Schottky Pickup (unit: mm)

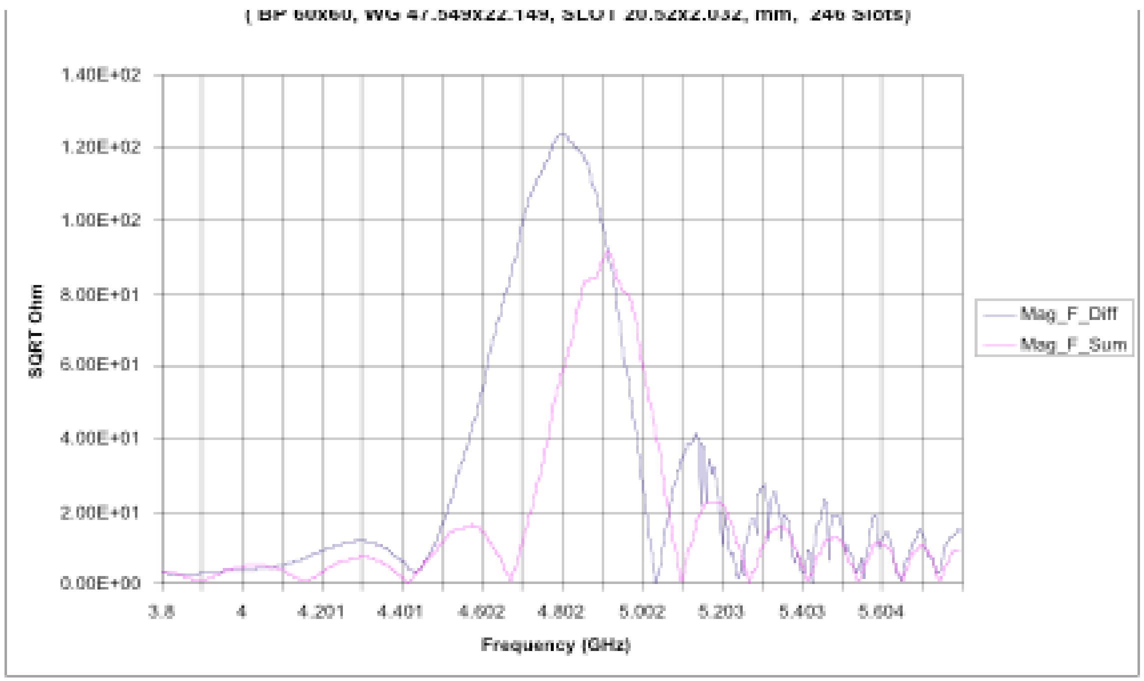
Slot length	Slot width	Slot Spacing	Number of Slots	Waveguide width	Waveguide height	Beam pipe width	Beam pipe height
20.52	2.032	2.032	246	47.549	22.149	60.00	60.00

Pickup and Adjacent Beampipe





Mode Launcher Impedance



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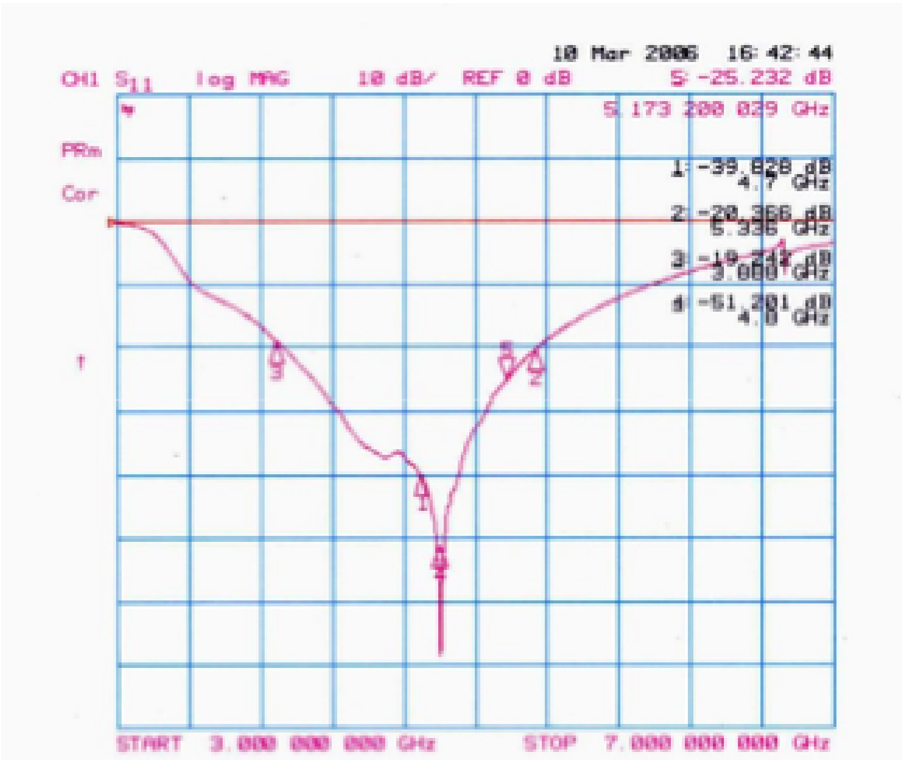
Mode Launcher Response



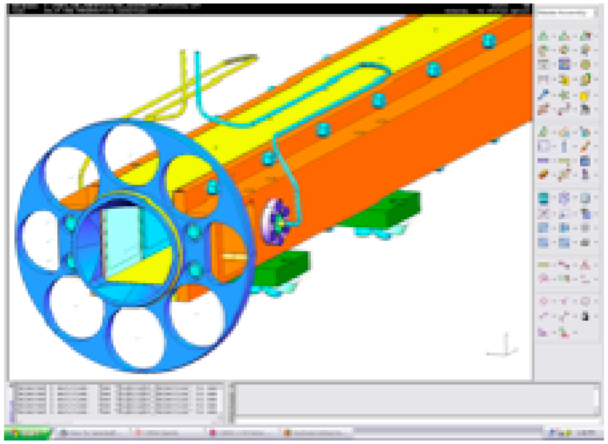
Connections and Processing

Feedthroughs and tunnel connections are critical

CERN ordering the coaxial cables

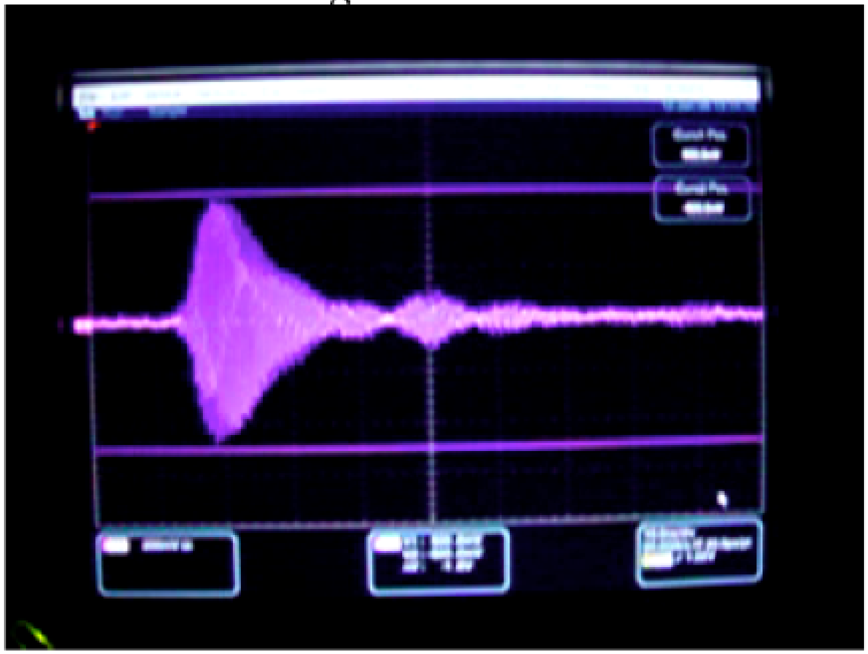
FNAL provided detailed layouts for phase matched cables

Installation planned in point 4 of LHC

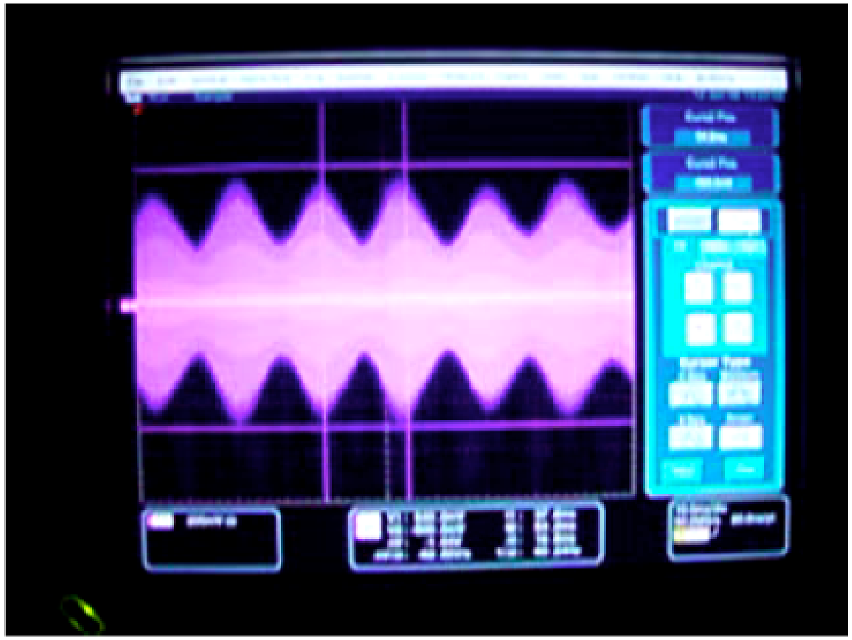


Tevatron Experience

Tevatron Single Bunch Horizontal Protons



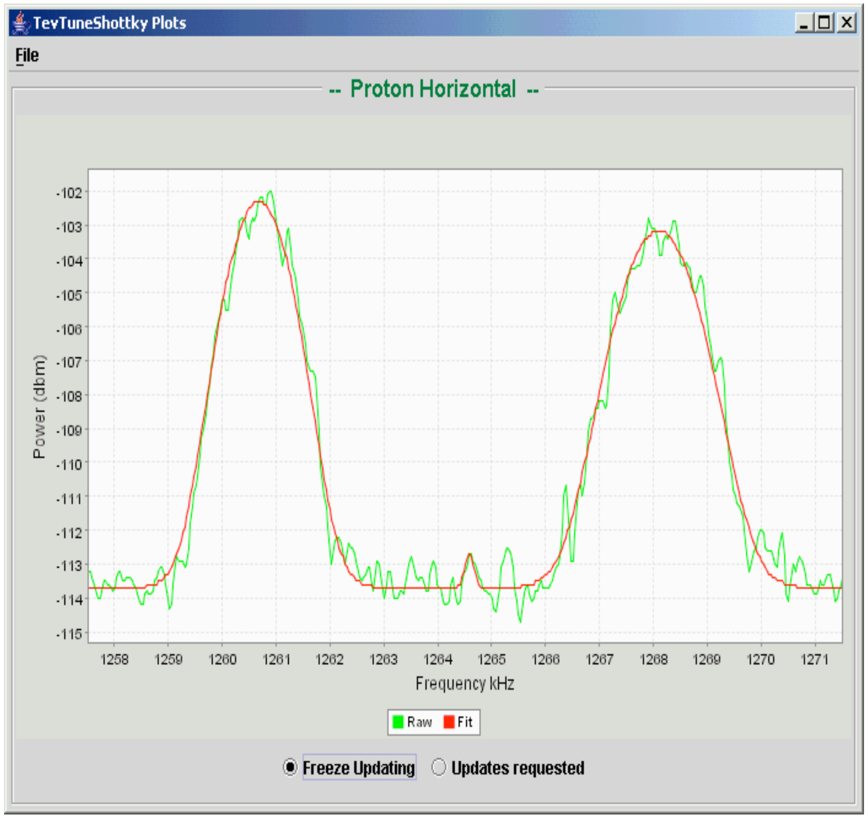
60 Hz Modulation on Tevatron Schottky Signals



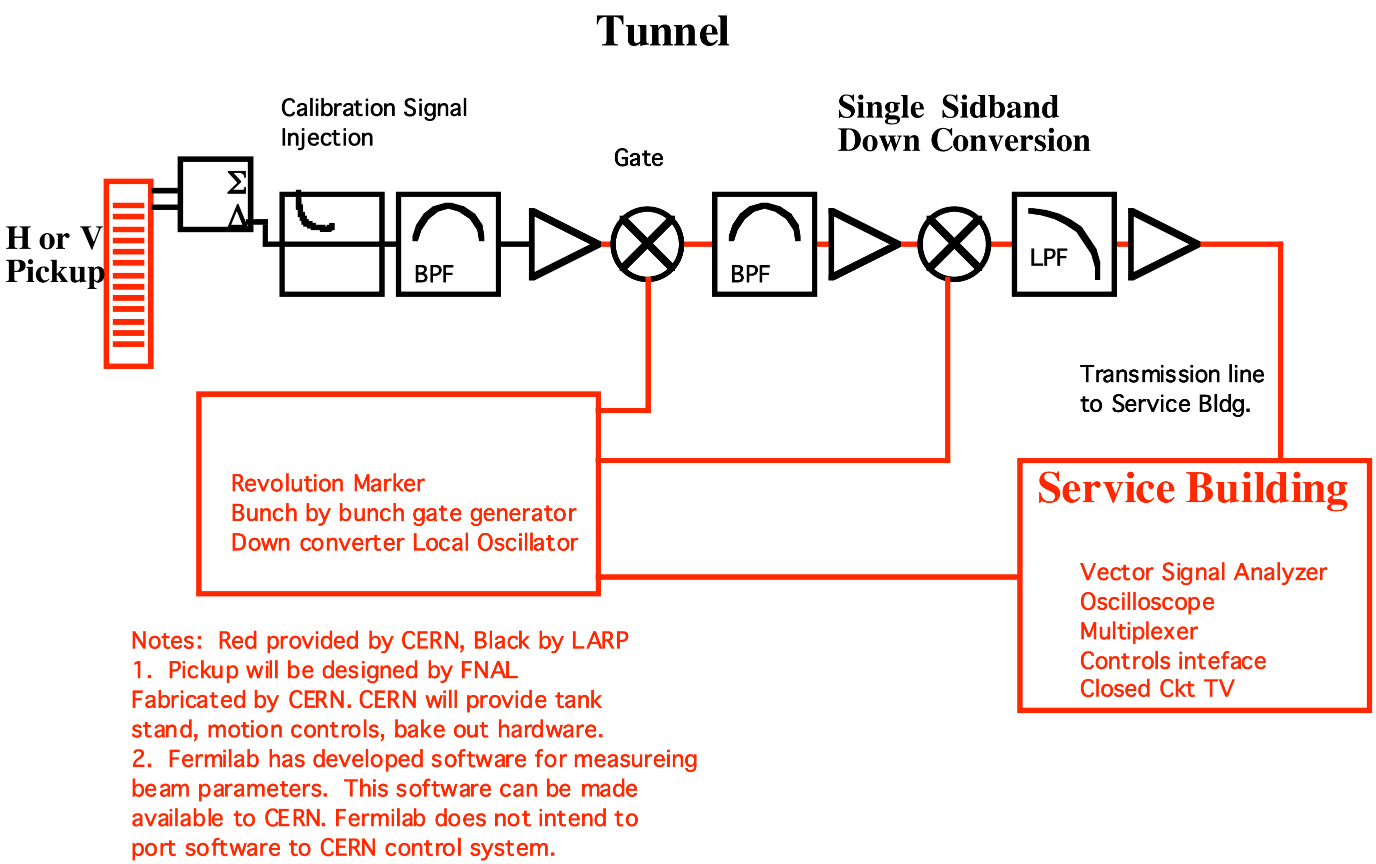
Schottky Measurements at Tevatron

Allows measurements of:

- Tunes from peak positions
- Momentum spread from average width
- Chromaticity from differential width
- Emittance from average band power



Schottky Electronics Block Diagram



Schottky Processing Electronics

Dual downconversion preserves single sideband signal with Chromaticity information

First IF at 45 MHz, using a LO locked to the 40MHz LHC clock reference

Crystal filter selects a 15 kHz band of schottky signal

Second IF takes the signal down to DC-80KHz baseband

Data is then collected with 20-24 bits CERN DAQ cards in DAB-IV environment

Schottky Monitor - Roles and Responsibilities

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FNAL/BNL

- Deliver a complete, ready to print drawing package to CERN
- Deliver a full set of front end electronics to connect to the detectors
- Provide installation and hardware commissioning support

CERN

- Build beamline devices to FNAL's prints
- Provide local cabling, installation,
- Local Oscillators, Reference signals, Data Acquisition hardware
- Final integration with control system

LARP - Commissioning

- The beam commissioning of these devices will be supported by the Beam Commissioning group

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Schottky Planning

FY06

Final Design Review at CERN on June 22

- Lots of other integration activities as well

CERN fabricates and installs the devices in the LHC

- Summer 2006, depending upon LHC's installation schedule
- All cables have been specified and requested
  - Including request for timing and synchronization signals

FNAL will build the analog processing electronics during the summer

FY07

Activities include hardware commissioning and installation support

In particular two trips to CERN, one to test the hardware without beam, and the next to test with beam (when beam occurs)

LUMI - Requirements

LARP

Requirements (Lumi mini Workshop, 16-17 Apr. 99)

- Absolute L measurement with $\delta L/L \sim 5\%$ for $L > 10^{30}\ cm^{-2}sec^{-1}$
- Cross calibration with LHC experiment measurements of L (every few months)
- Sensitivity of L measurement to variations of IP position ($x^*, y^* < 1mm$) and crossing angle ($x^{*\prime}, y^{*\prime} < 10\mu rad$) less than 1%
- Dynamic range with "reasonable" acquisition times for 1% precision to cover $10^{28} cm^{-2}\ sec^{-1}$ to $10^{34} cm^{-2}\ sec^{-1}$
- Capable of use to keep machine tuned within ~ 2% of optimum L
- Bandwidth 40 MHz to resolve the luminosity of individual bunches
- Backgrounds less than 10% of the L signal and correctable

LBNL 25 Jan. 2002 | 40 MHz Ionization Chamber W.C. Turner | 11

Help bring beams into collisions too

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LUMI - Specification

CERN
CH-1211 Geneva 23
Switzerland

the **Large Hadron Collider** project

LHC Project Document No. **LHC-B-ES-0007 rev 0.4**
CERN Div./Group or Supplier/Contractor Document No. **AB-BDI**
EDMS Document No. **347396**

Date: 2003-06-11

Functional Specification

MEASUREMENT OF THE RELATIVE LUMINOSITY AT THE LHC

Abstract

This functional specification defines the requirements for the measurement and optimization of the interaction rates or relative luminosity at the four LHC interaction points. The beam and machine scenarios and the anticipated uses in operation are analysed to define the required dynamic ranges, precision, time response,...of the machine luminometers. The potential for absolute calibration, the complementarities with the experimental absolute luminometers and the data exchange between machine and experiments are discussed and specified. The requirement for the measurement of the background to the experiments by standardized detectors was identified and will be dealt with in a separate document.

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J.P. Koutchouk/AB-BDI	*J-Jacques Gras [AB/BDI]*	
M. Placidi/AB-BDI	*Rüdiger Schmidt [AB/CO]*	
E. Tsesmelis/EST-LEA	*Jörg Wenninger [AB/OP]*	

Approval Group Members

LTC: S. Myers, P. Collier; AB/ABP: J.-P. Riunaud, S. Fartoukh, W. Herr, F. Ruggiero;
AB/BDI: H. Schmickler, R. Jung, E. Bravin, W.C. Turner; AB/OP: S. Baird, K. Cornelis;
EST/LEA: K. Potter;
ALICE: D. Evans, C. Fabjan, L. Leistam, A. Morsch; ATLAS: N. Ellis, P. Grafstrom, M. Nessi;
CMS: A. Ball, A. Herve, M. Huhtinen, W. Smith; LHCb: R. Jacobsson, A. Smith, W. Witzeling;
TOTEM: M. Bozzo, K. Eggert, D. Macina, M. Oriunno;

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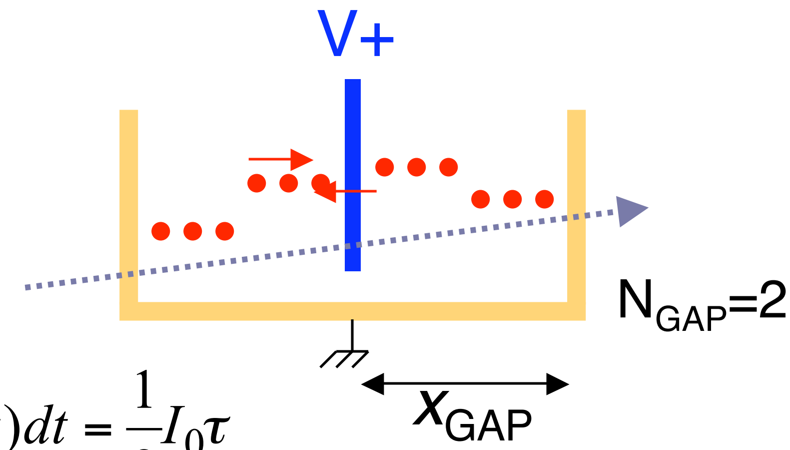
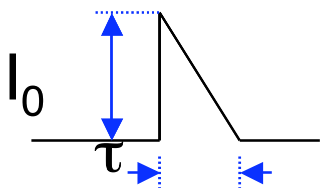
LUMI - Conceptual Design
Argon Ionization Chamber





$$\tau = x_{GAP}/v_D \qquad Q = \int_0^{\tau} I(t)\,dt = \frac{1}{2} I_0 \tau$$

Signal is proportional to the number of parallel gaps
Capacitance add up with n. of gaps + slows down the signal

→Optimized for 6 gaps
→Must live in a radiation environment 100x worse than accelerator instruments have ever seen

→~10Gy/yr, ~10^{18} N/cm^2 over lifetime (20 yrs), ~10^{16} p/cm^2 over lifetime

LUMI Status

Final design complete

- Successful design review on April 24, 2006

Most critical R&D parameters demonstrated

- Successful high speed (40 MHz test) using X-ray beamline at ALS

Final design presented here

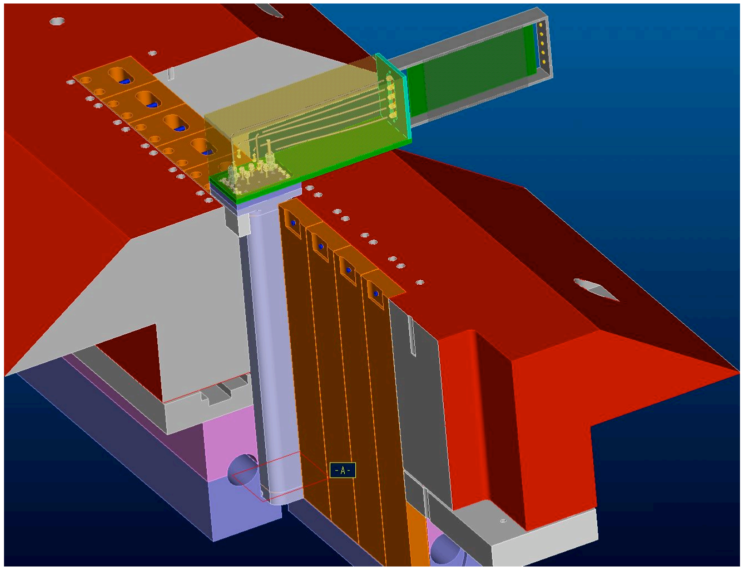
Some R&D still ongoing

- Testing prototype in RHIC
- Rad damage tests underway

FDR results

Excellent review

- Highlighted several areas of possible improvement
- Endorsed basic design
- Recognized progress
- Recommended fast path to production



Final report not available yet

Testing at RHIC

- RHIC run was suddenly restored
- Presented plan at RHIC APAX meeting in November
  - Asked for 2 shifts of 3-4 hours each
    - Need dedicated collisions
- Now setup in IR10, former PHOBOS area
- While ideal running condition is Au-Au, this run is p-p
  - We’ll focus on backgrounds and on establishing operation of the device - 250 GeV will help
- Infinuim scope we can watch from LBL
  - Plan to use in parasitic mode while RHIC is running
  - Plan to replace with lumi DAQ system

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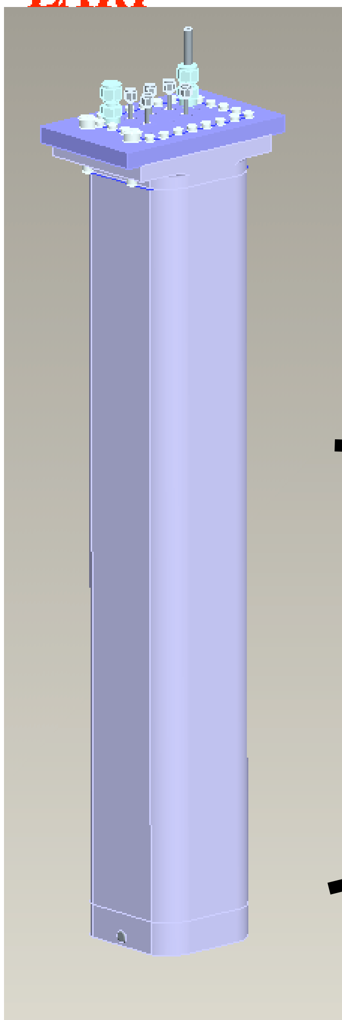
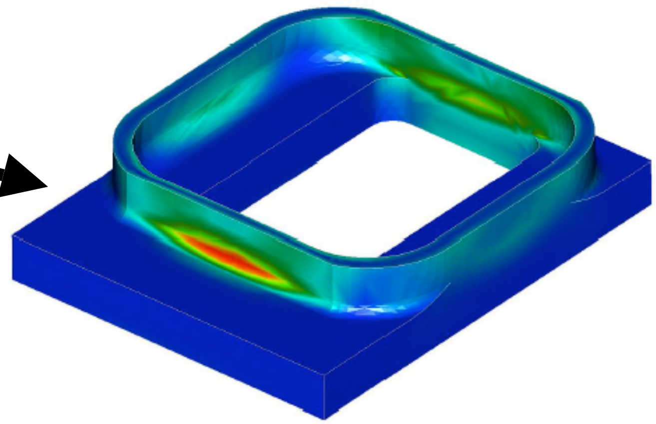
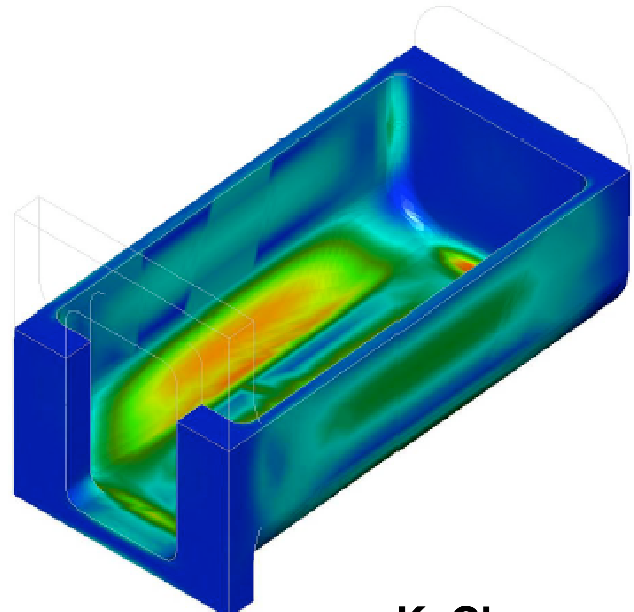
Mechanical Design

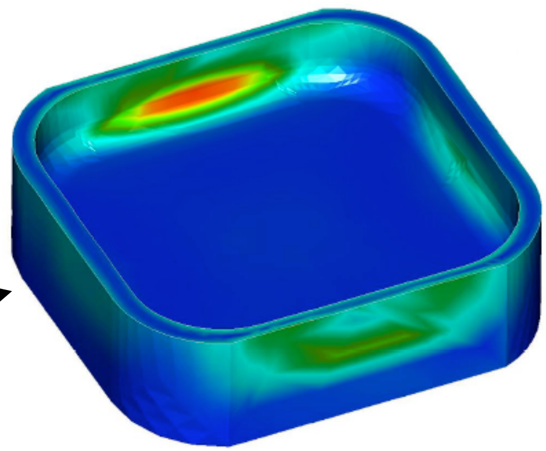
- Ready for final prints and production
- Performed thermal and stress analysis
- Performed gas flow modeling through the chamber
- Completely revised the housing and fabrication
  - Detector nearly identical to the prototype
- Fabrication process defined

Case is designed to manage stress levels







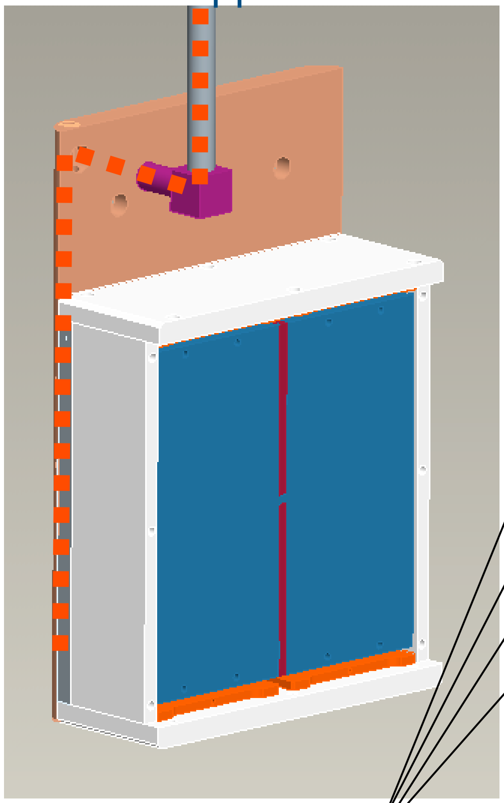


K. Chow

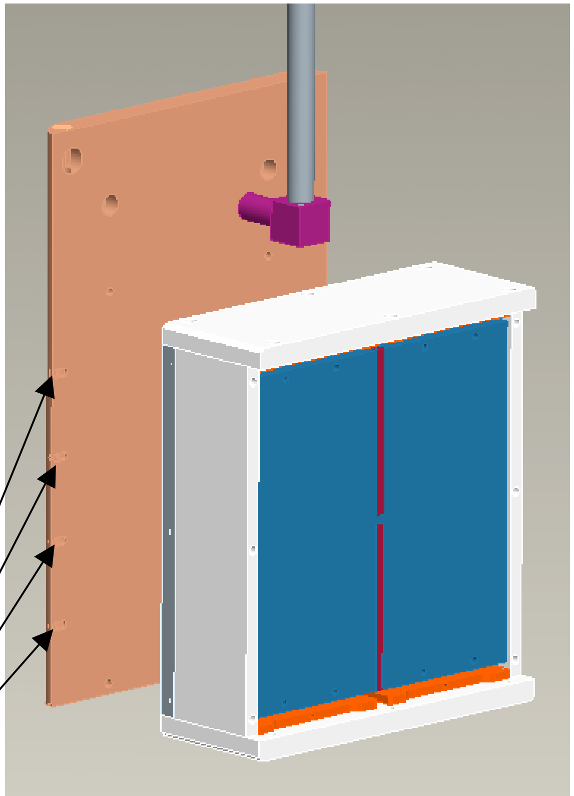
Max stress is <16kpsi (<110 MPa)

Gas flow through ionization chamber

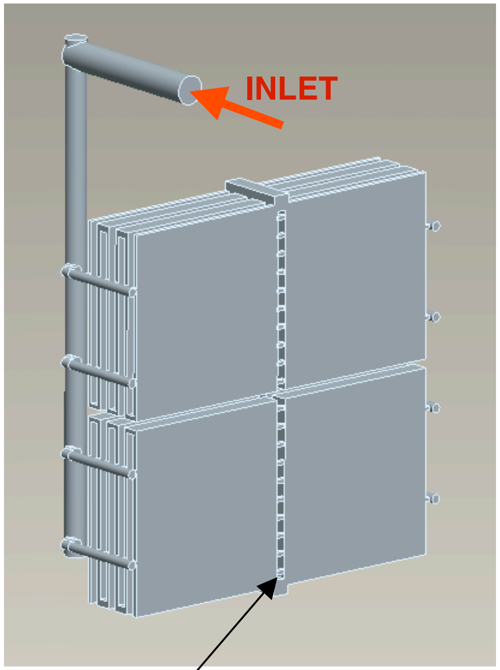
Detail of ionization chamber without copper bar



With support plate displaced in beam direction



Chamber gas flow volume model



4 gas inlet holes on support plate

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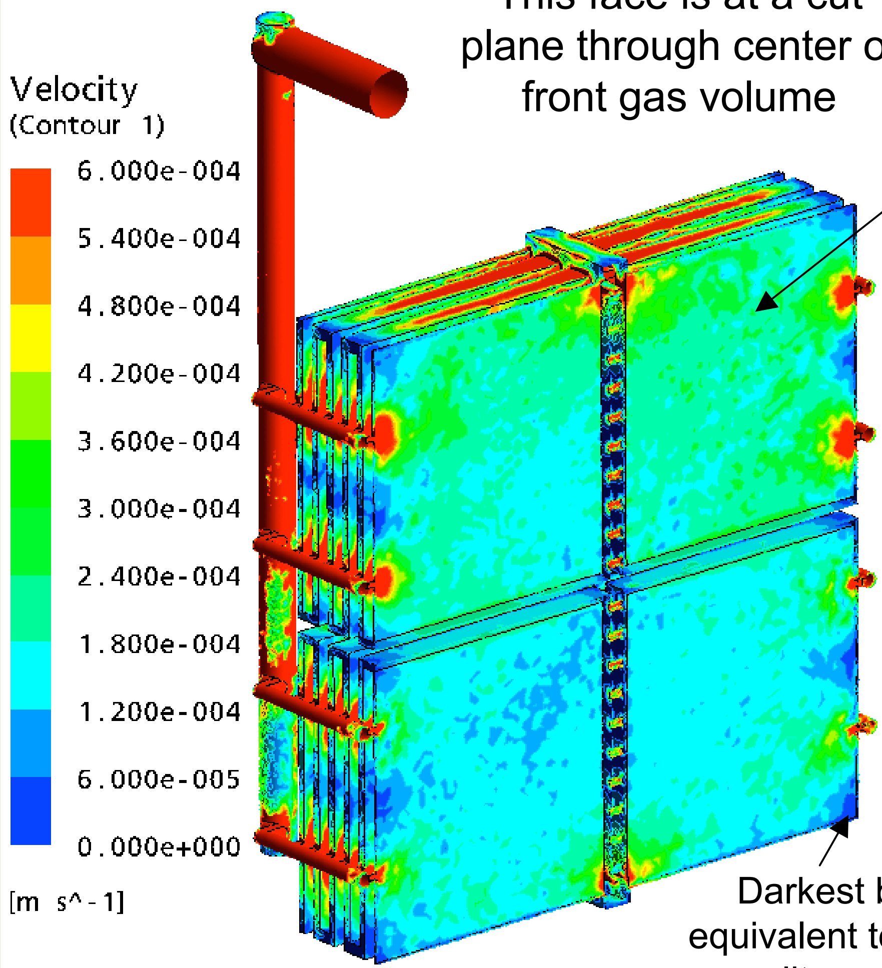
120 holes in ground plane, 1 mm diameter each

Gas velocity in production chamber



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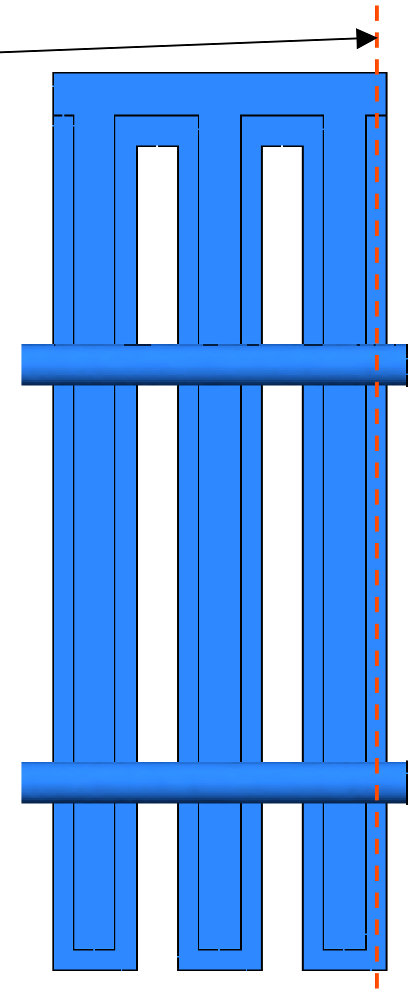
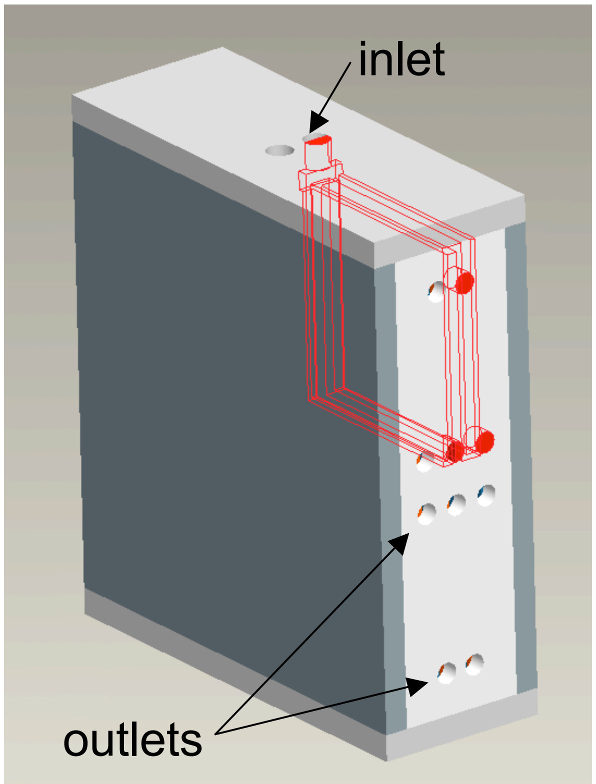
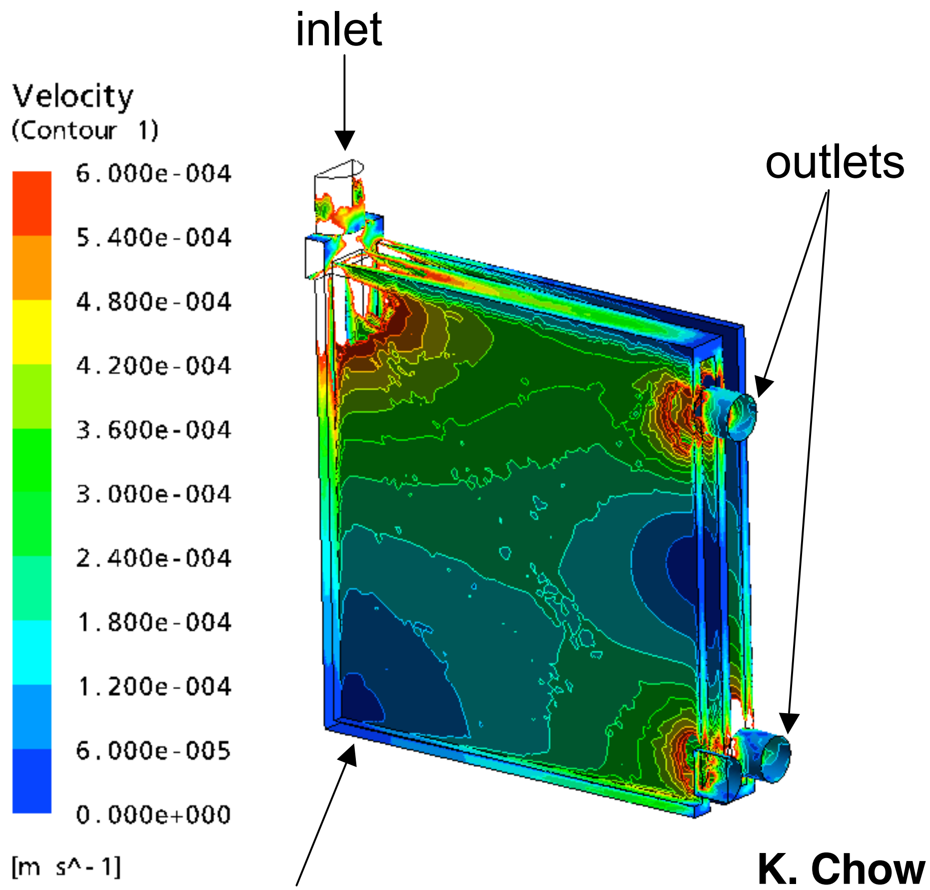


For comparison: gas velocities in prototype chamber

Prototype ionization chamber showing outline of 1/8 symmetric gas flow model





K. Chow

Darkest blue areas are equivalent to less than 0.017 liter per hour flow

Thermal conditions during TAN bakeout

Bakeout operation

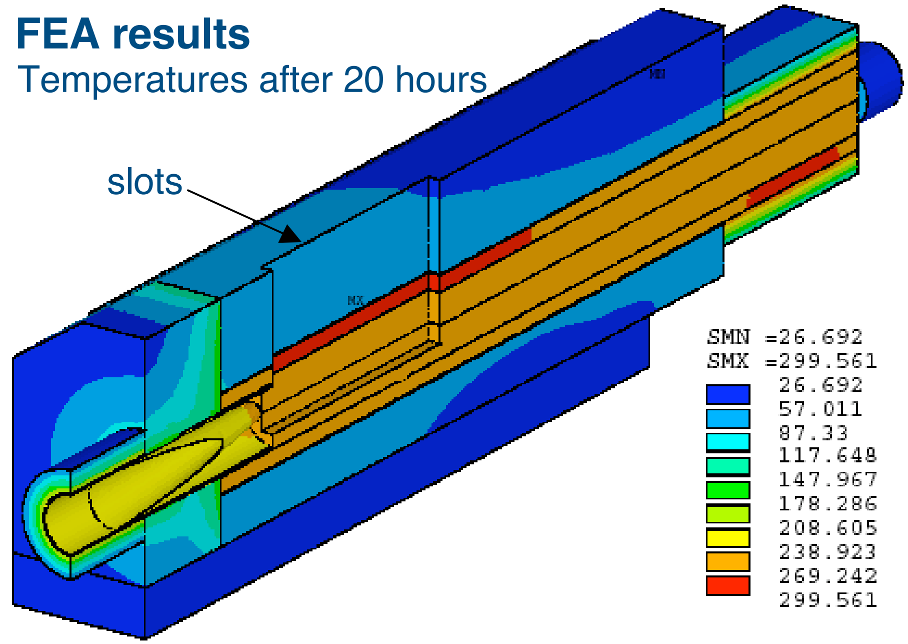
- Heat up the beam tube to 200 deg C in 24 hours.
- Stay at 200 deg C for a minimum of 24 hours
- Ambient cooldown

Bakeout performed in situ whenever beam tube exposed to atmospheric pressure

Maximum temperature in absorber box is up to 300 deg C

FEA results

Temperatures after 20 hours



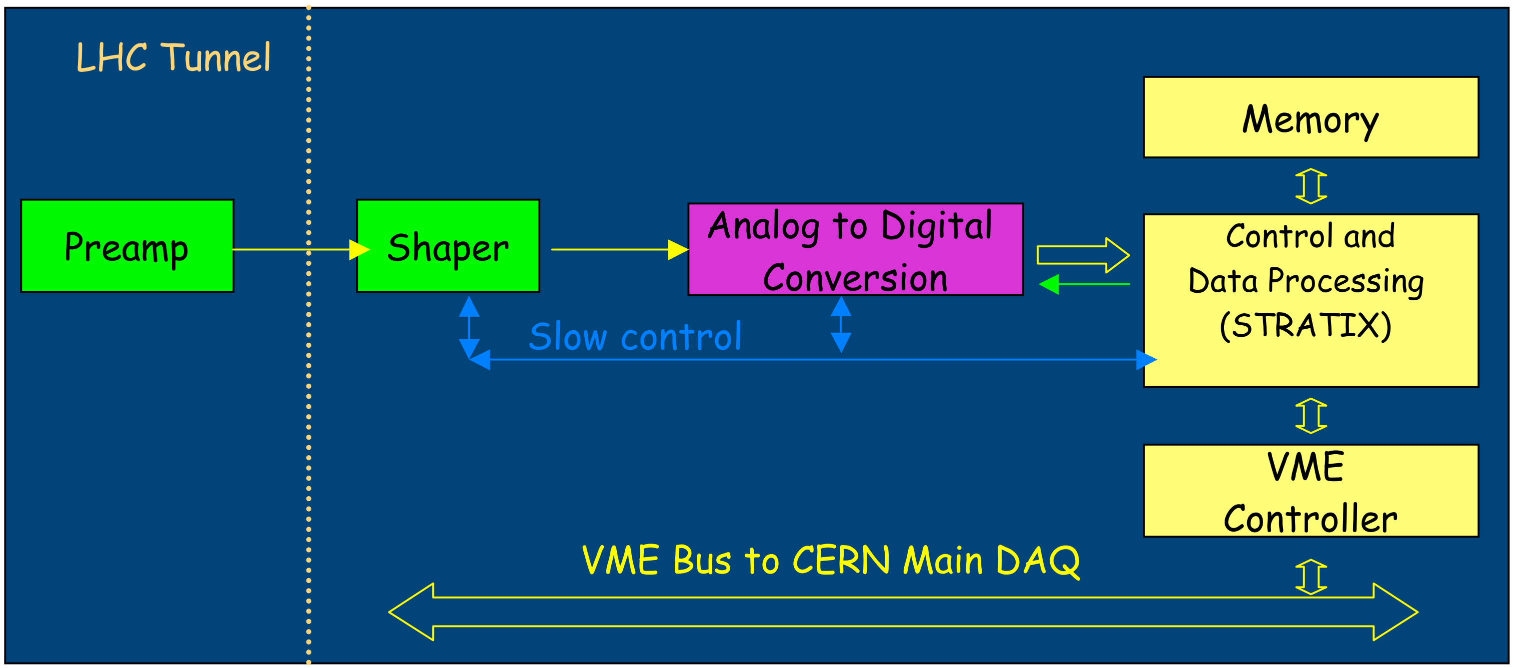
Details of the handling plan for LUMI are being formulated

K. Chow

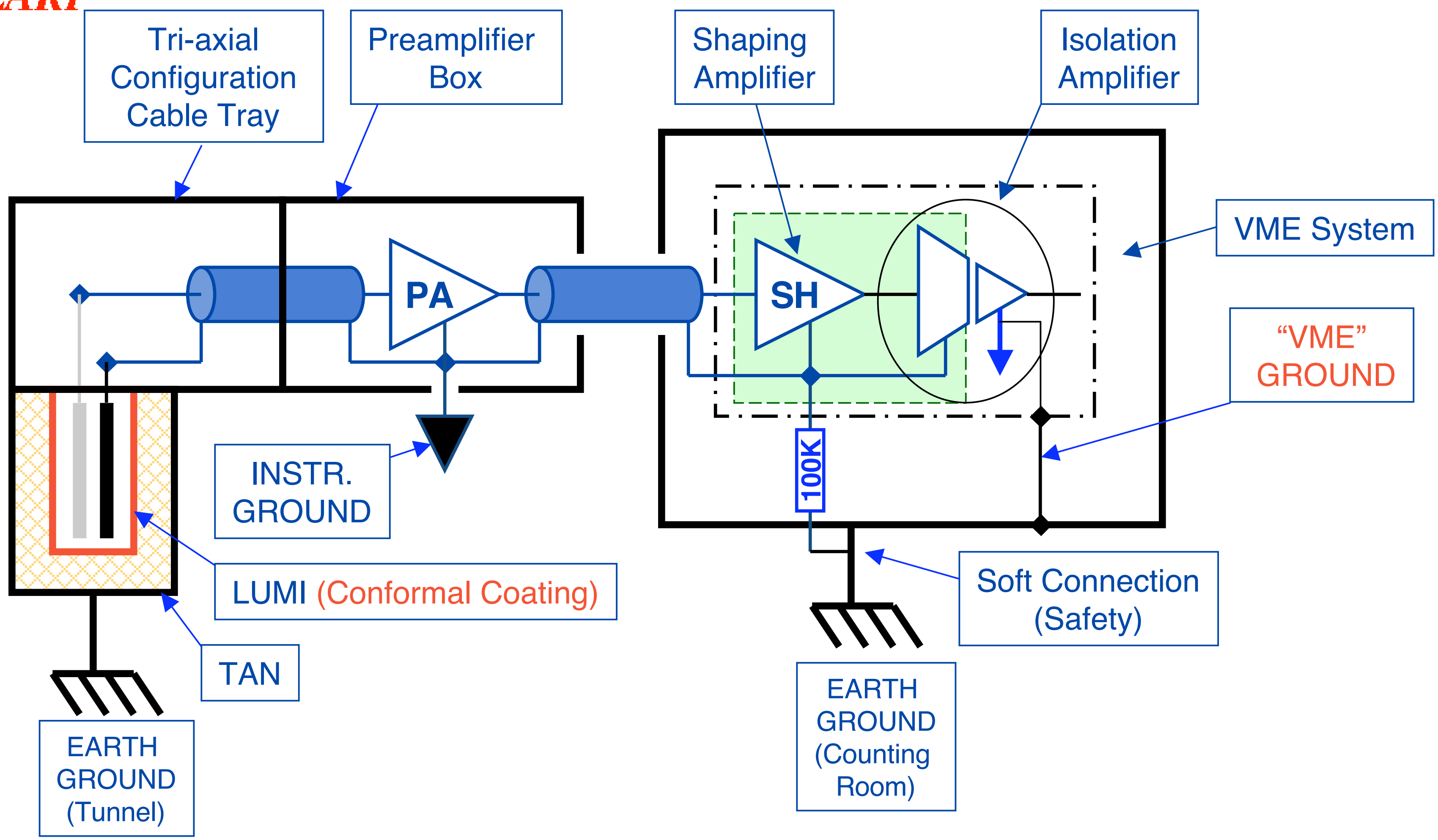
- Analysis will be used to estimate temperature rise in LUMI
- Temperatures in LUMI should be monitored during bakeout (with thermocouples) to determine if it exceeds its allowable temperature
- LUMI should be (partially) pulled out of slot if it may overheat (pullout has radiation exposure implications)

Signal Processing

- Very low noise pre-amp in the tunnel
- Shaper section completes the analog signal processing
- ADCs integrated in a VME64 mezzanine card
  - Interface defined by CERN BDI group



Electrical Connections



IBMS Mezzanine Board (1)

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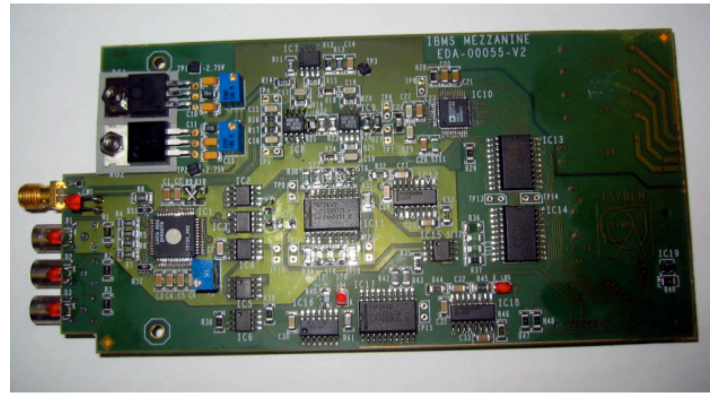
Data from IBMS technical specifications document in EDMS (Jean-Jacques SAVIOZ)

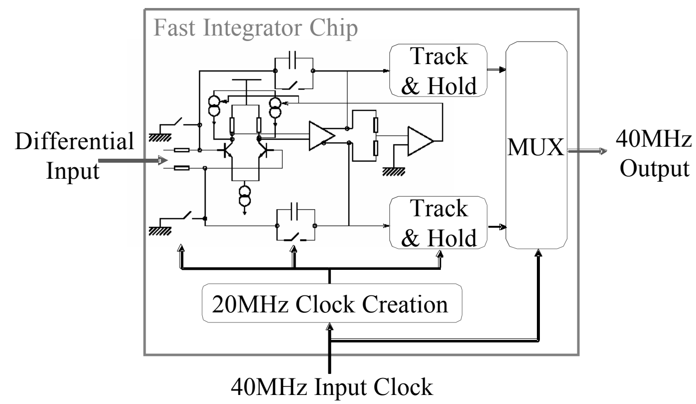


IBMS Mezzanine Board contains:

- Custom ASIC originally developed for the LHCb Preshower detector
- 14-bit digitizer (only 12 used).

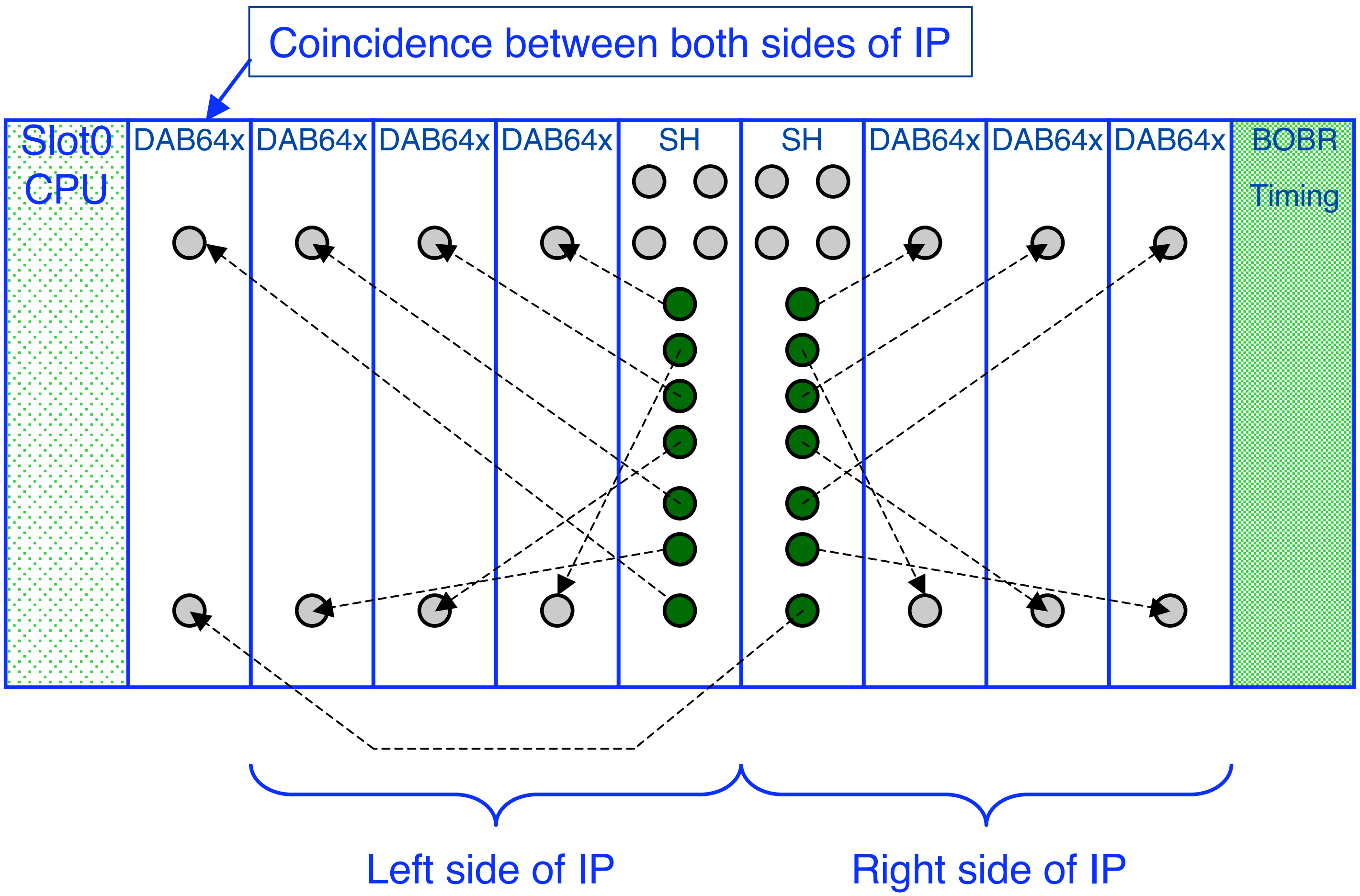
ASIC:

- Dual integrator + T/H circuit
- One integrator operates while other is in reset mode.



Differential input.

Shaper Board and DAB64x boards



Radiation Damage to passive components

- Damage to passive components is mostly dominated by neutron scattering
- DPAs are a best way to measure the effects of radiation exposure
- While a DPA to first order is a DPA, neutron energy, flux, temperature changes can have a great impact on test results
    - If an atom is displaced and quickly recombines, it could be no problem
    - If this happens while an enormous amount of heat is dissipated, the material properties could easily change, the atom may not recombine…
- Using the DPA approach, we can use neutrons at several test facilities
    - Still important to have relatively high energies

Rad Damage Testing at CERN

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- At the ISOLDE ion source with a 1.4 GeV p beam from CERN PS Booster
  - ~10^13 protons per second
- Facility has robotic capabilities
- Have prepared two identical kits
- First kit will be exposed ~3 months
- Second kit will be exposed ~ 9 months
- After irradiation we will perform mechanical testing and metallurgical investigations of the samples.
  - Electrical components are in a bridge configuration for easy electrical measurements
- Setting up a MARS model to calculate DPAs in this configuration and compare with LHC projections

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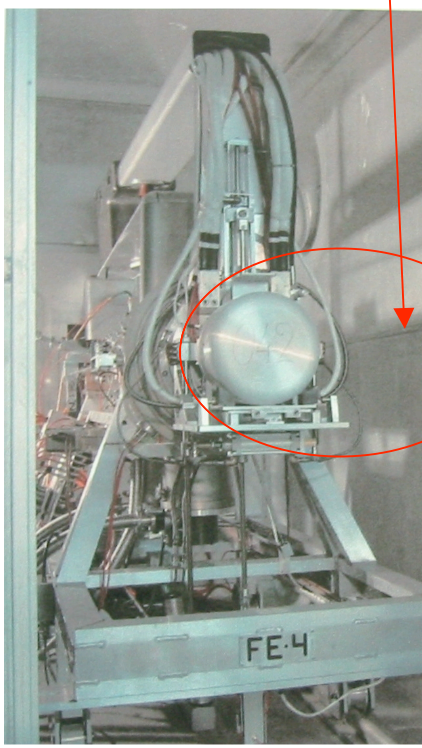
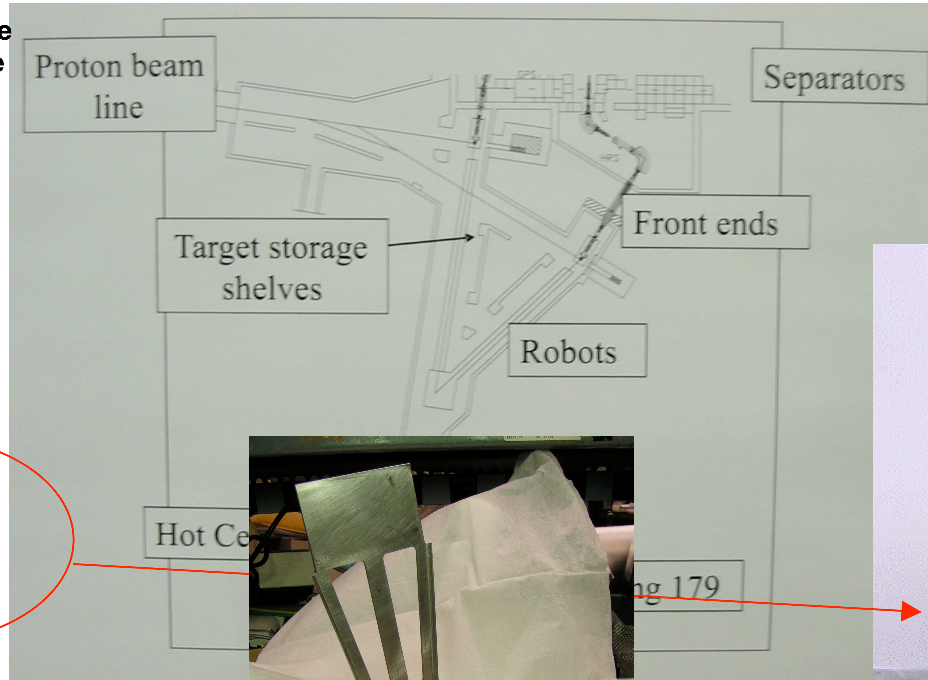
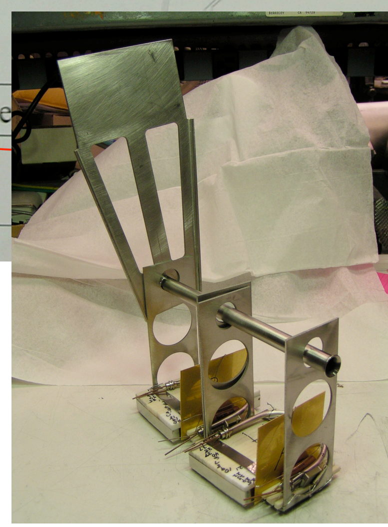
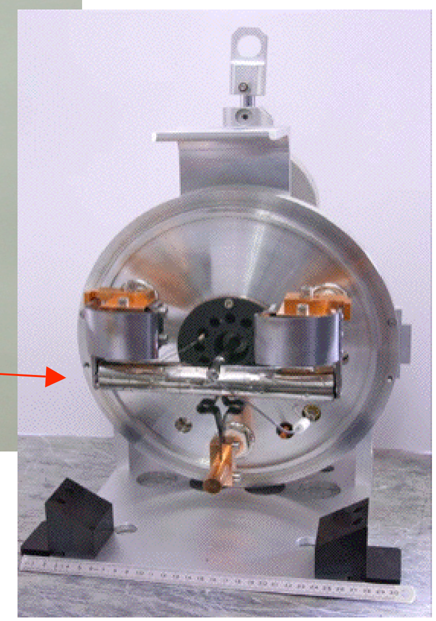
Setup at ISOLDE's source

Our samples are mounted on the wall behind the source









Active Components in LUMI

In general a level of ~100 krad/yr is tolerated by bipolar transistors

Packaging front end electronics for fast replacement

- Dual channel to overcome random failures

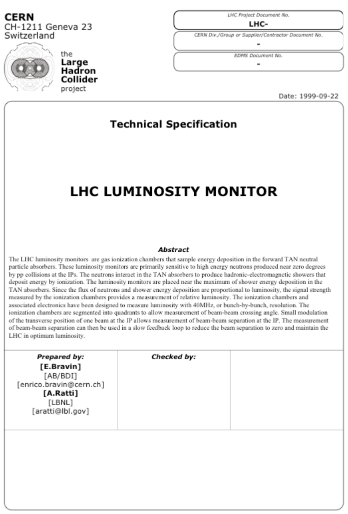
Recommend replacement after a given integrated dose

- 1-2 years at highest luminosity
- Earlier operation at lower luminosity will allow for a longer time before replacement

Do we have a choice??

Integration planning at CERN

- Complete system description
  - Technical, installation, safety, electronics, responsibilities, deliverables…
- Met with all relevant parties at CERN
- Final draft at CERN
- EDMS process underway



CERN
CH-1211 Geneva 23
Switzerland

the **Large Hadron Collider** project

LHC Project Document No.
LHC-

CERN Div./Group or Supplier/Contractor Document No.
-

EDMS Document No.
-

Date: 1999-09-22

Technical Specification

LHC LUMINOSITY MONITOR

Abstract

The LHC luminosity monitors are gas ionization chambers that sample energy deposition in the forward TAN neutral particle absorbers. These luminosity monitors are primarily sensitive to high energy neutrons produced near zero degrees by pp collisions at the IPs. The neutrons interact in the TAN absorbers to produce hadronic-electromagnetic showers that deposit energy by ionization. The luminosity monitors are placed near the maximum of shower energy deposition in the TAN absorbers. Since the flux of neutrons and shower energy deposition are proportional to luminosity, the signal strength measured by the ionization chambers provides a measurement of relative luminosity. The ionization chambers and associated electronics have been designed to measure luminosity with 40MHz, or bunch-by-bunch, resolution. The ionization chambers are segmented into quadrants to allow measurement of beam-beam crossing angle. Small modulation of the transverse position of one beam at the IP allows measurement of beam-beam separation at the IP. The measurement of beam-beam separation can then be used in a slow feedback loop to reduce the beam separation to zero and maintain the LHC in optimum luminosity.

Prepared by:	*Checked by:*	
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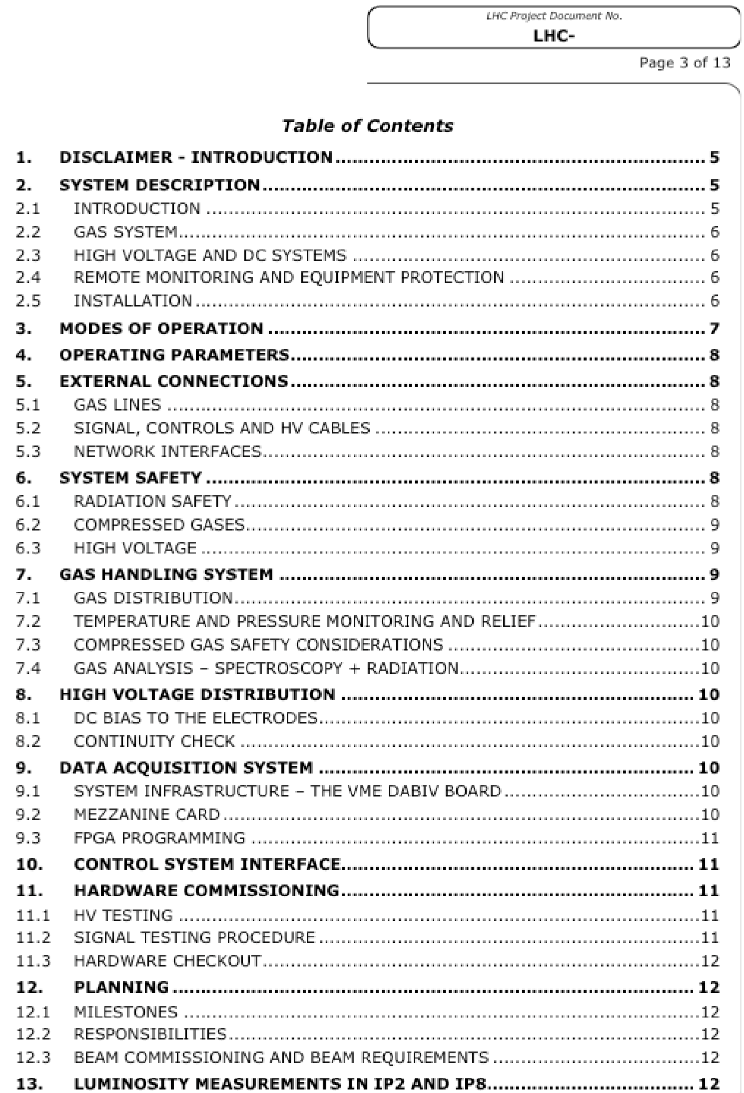

LHC Project Document No.
LHC-

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Integration effort at CERN

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~8 FTE-months spent at CERN in integration activities

Two integration meetings in January and March

- Including an integration workshop with all groups instrumenting TAN

Opening a team account to support local expenses

Planning more visits to further plans and follow through

TS/LEA group now responsible to coordinate installation and documentation of TAN instrumentation area

- Generates 3D layout of the area
- Coordinates gas installation activities

LUMI Long Term Plans
(from 2005)

FY06

- Fabrication of first article
- Design of auxiliary hardware
- Device tests, electronics integration and performance qualification
- Deliver first unit to CERN - delayed ~3 months

FY07

- Fabricate balance of units and auxiliary hardware
- Transfer to CERN
- Installation support
- Commissioning support

FY08

- Post-commissioning and pre-operations support

Tune Feedback

LARP

Challenge: persistent current effects in SC magnets can strongly perturb machine lattice, especially during energy ramp (aka “snapback”). Effects for LHC predicted to be large.

Betatron tunes ($Q_{x,y}$) and chromaticities ($Q'_{x,y}=EdQ_{x,y}/dE$) can vary significantly due to “snapback” resulting in beam loss, emittance growth.

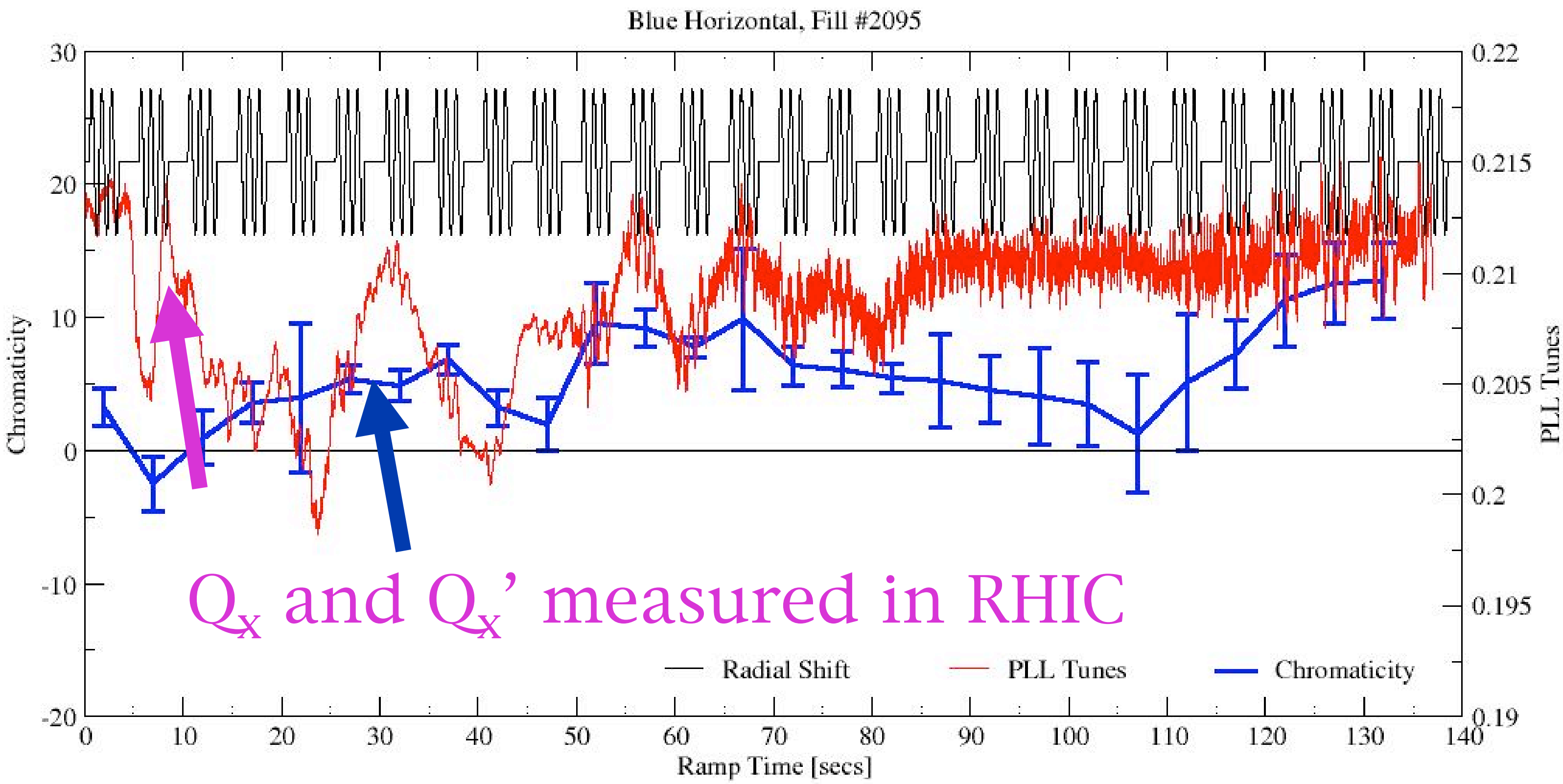
Solution: make fast, precision Q, Q’ measurements and use these signals to feedback to tuning quadrupoles and sextupoles.

This effort is ideally suited for a collaboration with RHIC, which can be the benchmark and testing ground for this effort.

The Two Issues at RHIC:

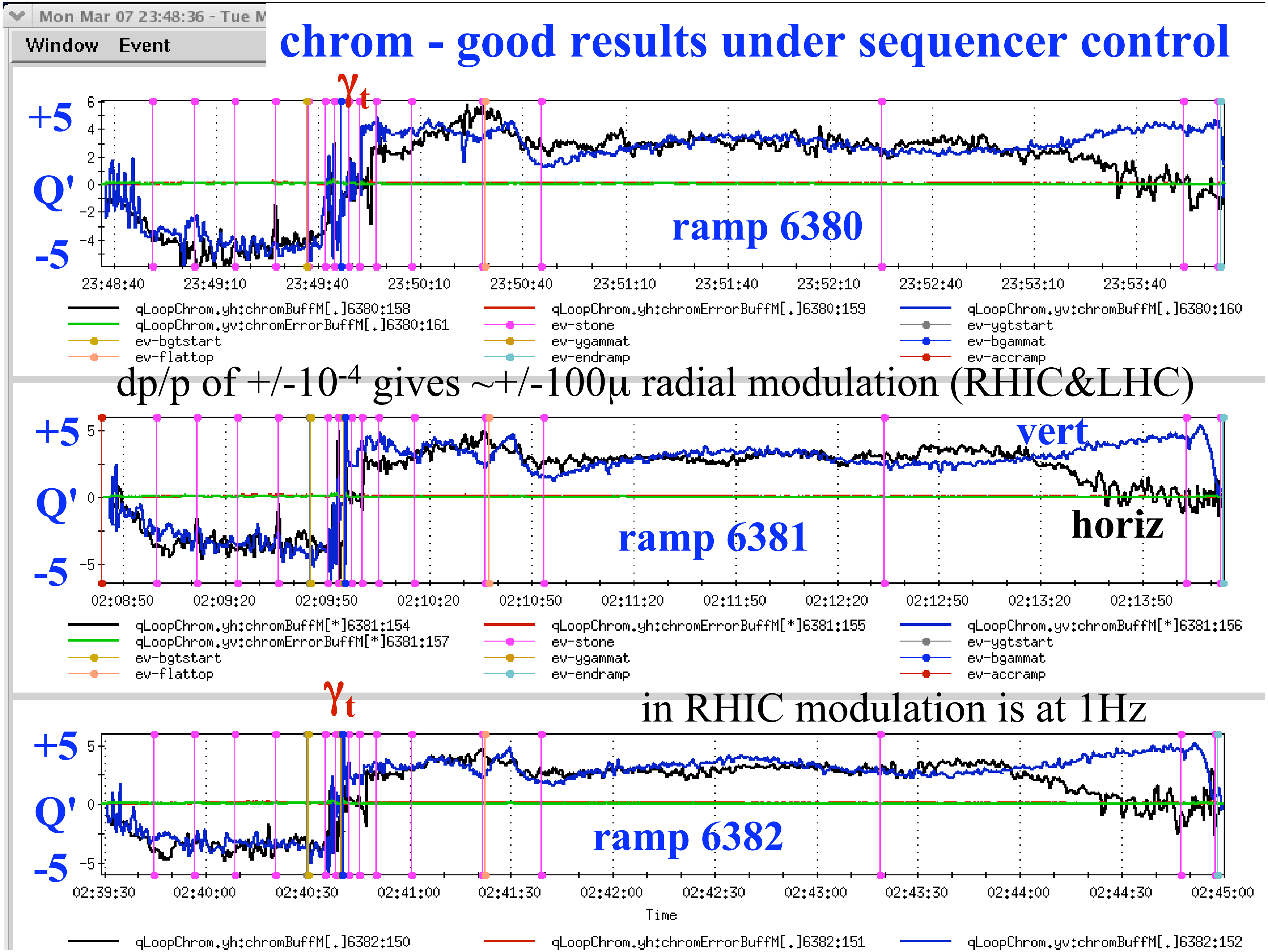
- Dynamic Range
- Coupling

Effects of persistent currents in RHIC
(early results)



Energy increasing

chrom - good results under sequencer control



LARP

Tune Feedback - Technical Approach

Previous RHIC approach

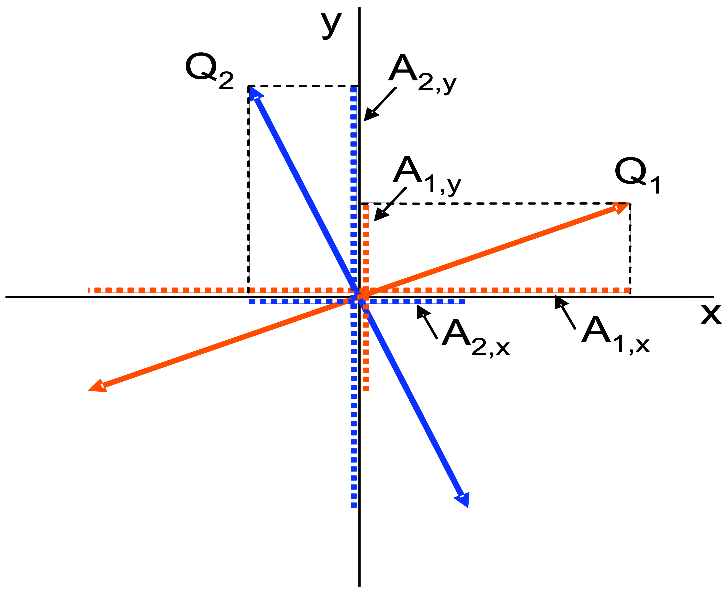
- resonant pickup, above the coherent spectrum
- defeated by transition - short bunches, fast orbit changes
- defeated by coupling - strong sextupoles, vertical orbit changes affect coupling, coupling drives tune feedback unstable

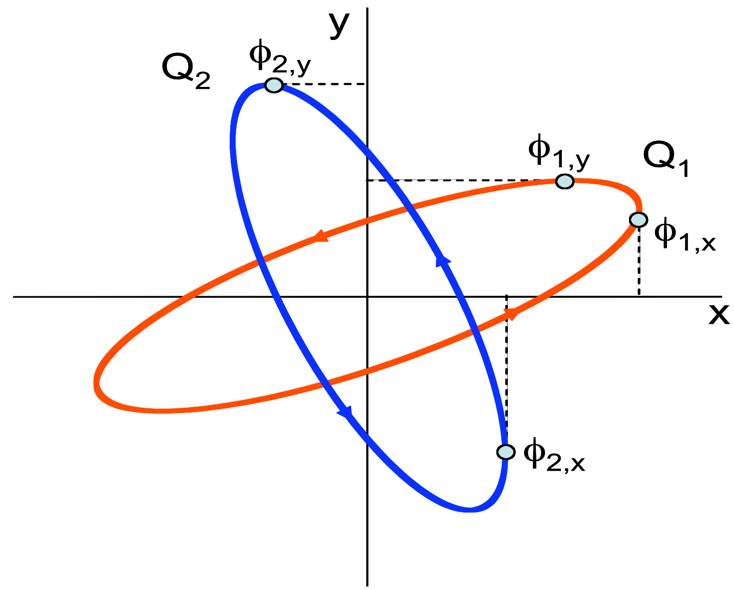
New LHC (and current generation RHIC)

- direct diode detection - mix all betatron lines to baseband, solves dynamic range problem
- measure all four eigenmode projections - results in PLL that is robust in the presence of coupling

CERN and BNL personnel are actively collaborating on tune feedback and using RHIC as a platform for developing the system

Effects of Coupling





Schematics showing the two eigenmodes rotated with respect to the horizontal and vertical planes due to coupling. The left hand figure shows the special case where the projections of each mode in each plane are in phase. The right hand side shows the more general case where coupling introduces a phase shift into the eigenmode projections.

C-A/AP/174 - Possible phase loop for the global betatron decoupling, Y. Luo et al
C-A/AP/204 - Towards a Robust Phase Locked Loop Tune Feedback System, R. Jones et al
both at http://www.rhichome.bnl.gov/AP/ap_notes/cad_ap_index.html

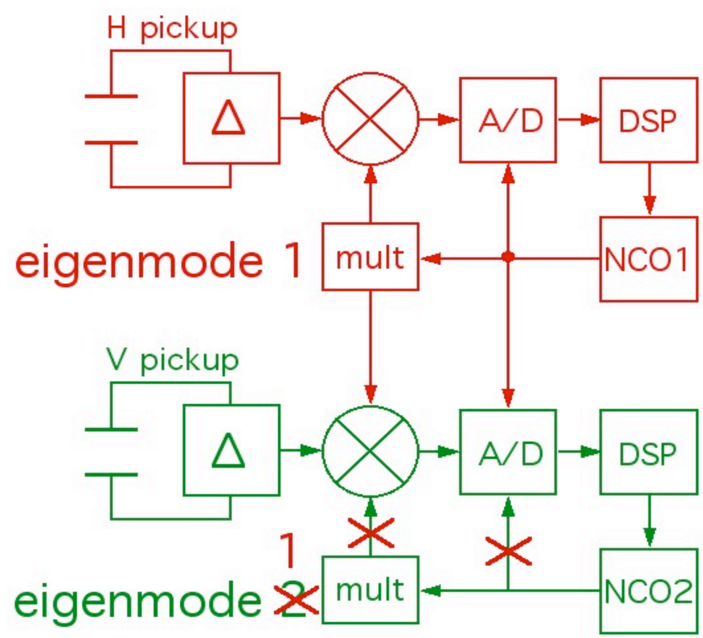
Tune and Coupling Measurements

Tune

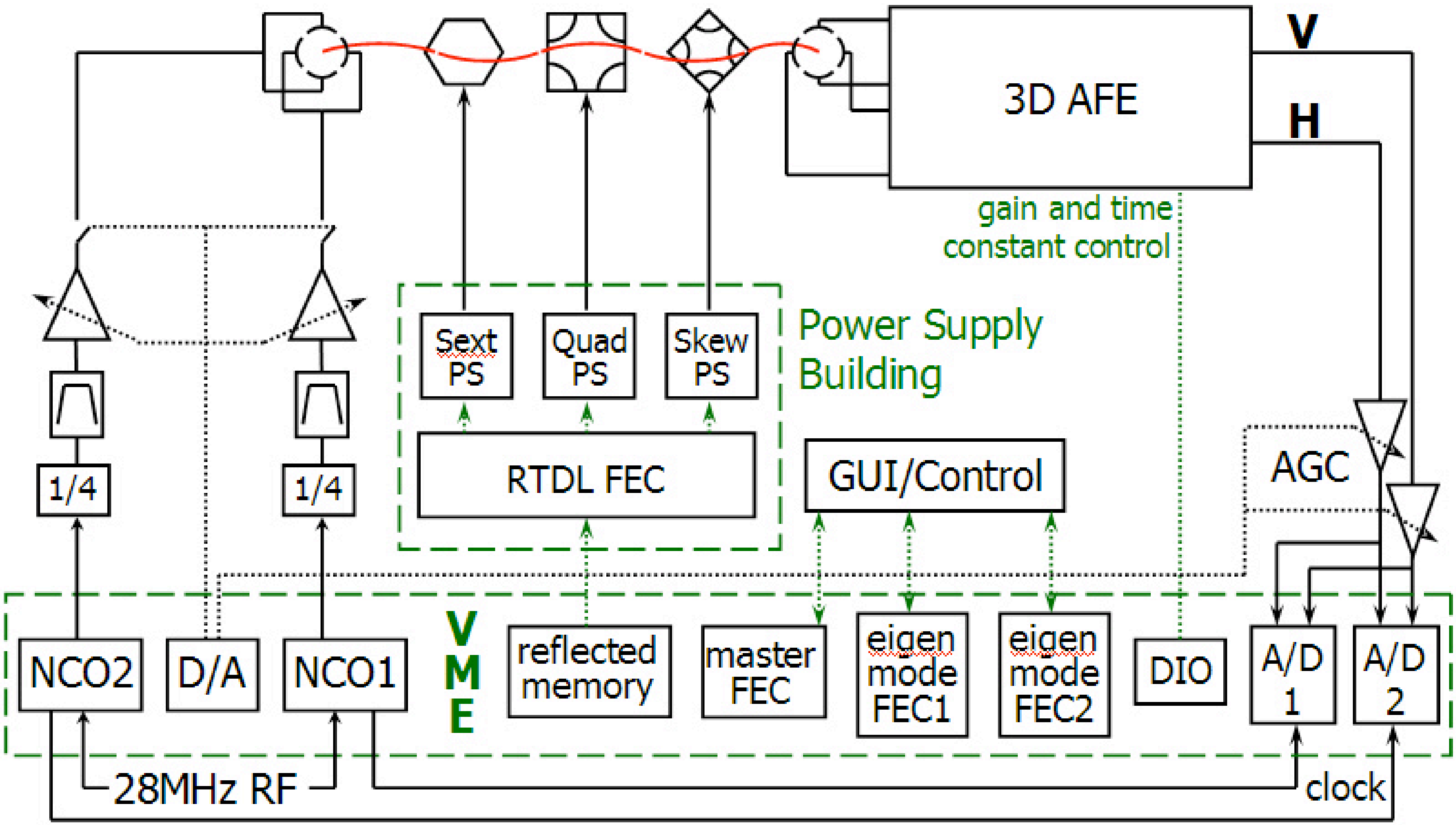
- PLL tune measurement operational at RHIC for several years, automated, controlled by sequencer. Specialist checks status every few days.
- Used for ramp tune and chrom measurements, IR corrections, machine studies,...

Coupling

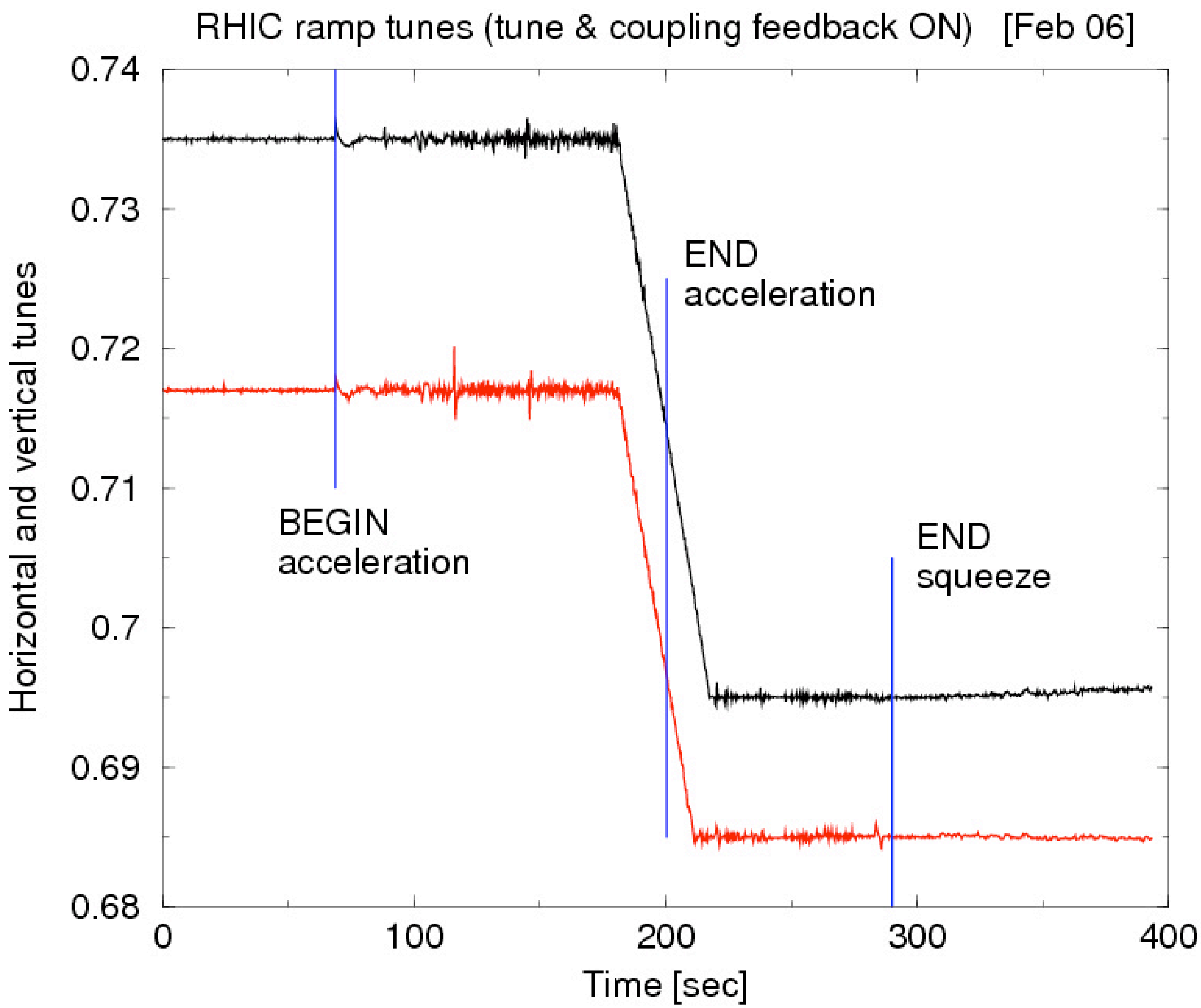
- PLL re-configured to measure all four eigenmode projections
- results in PLL that can be made robust in the presence of coupling



RHIC Systems Diagram



Recent Success at RHIC



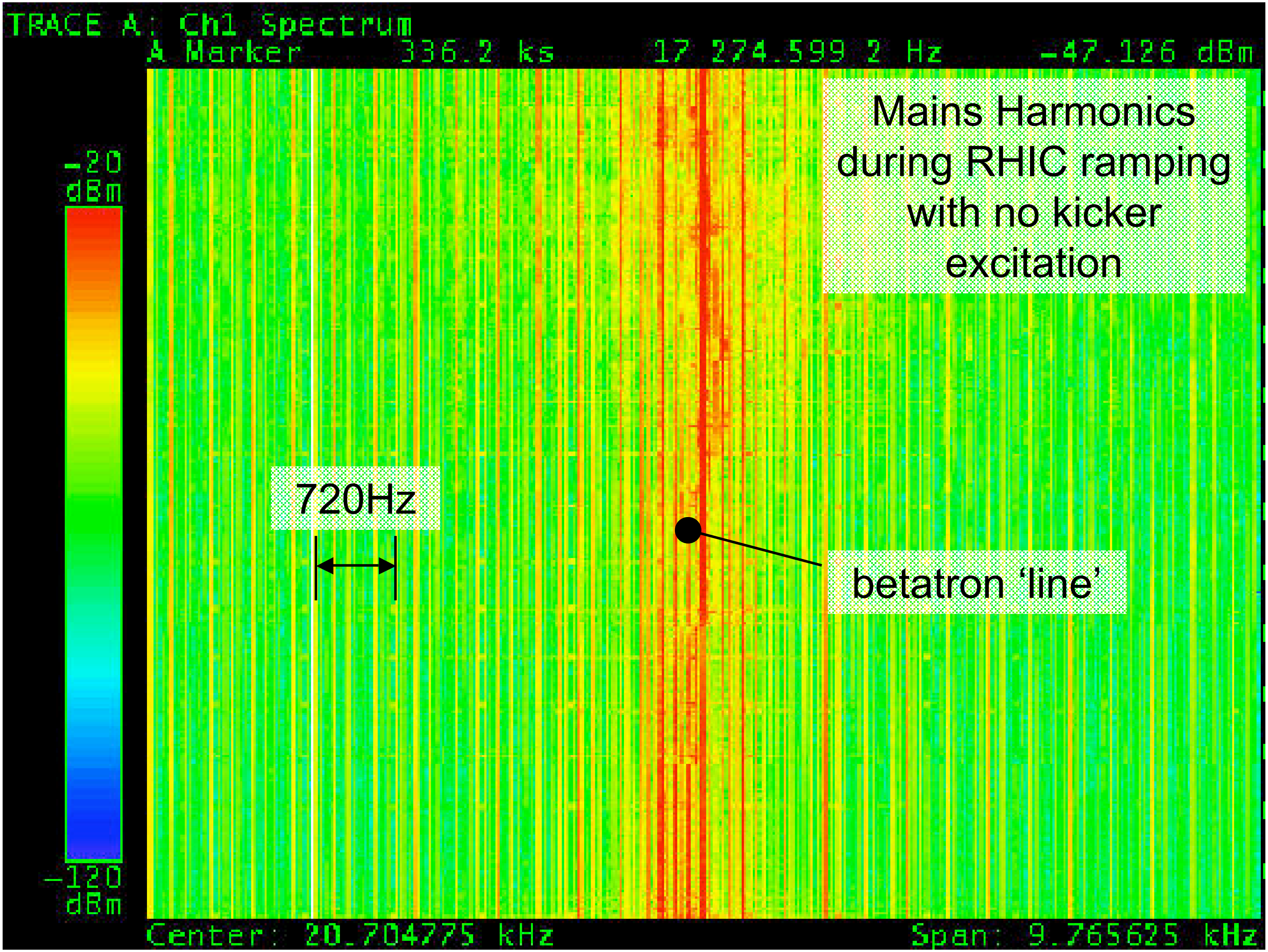
Tune Feedback - Ongoing Activities

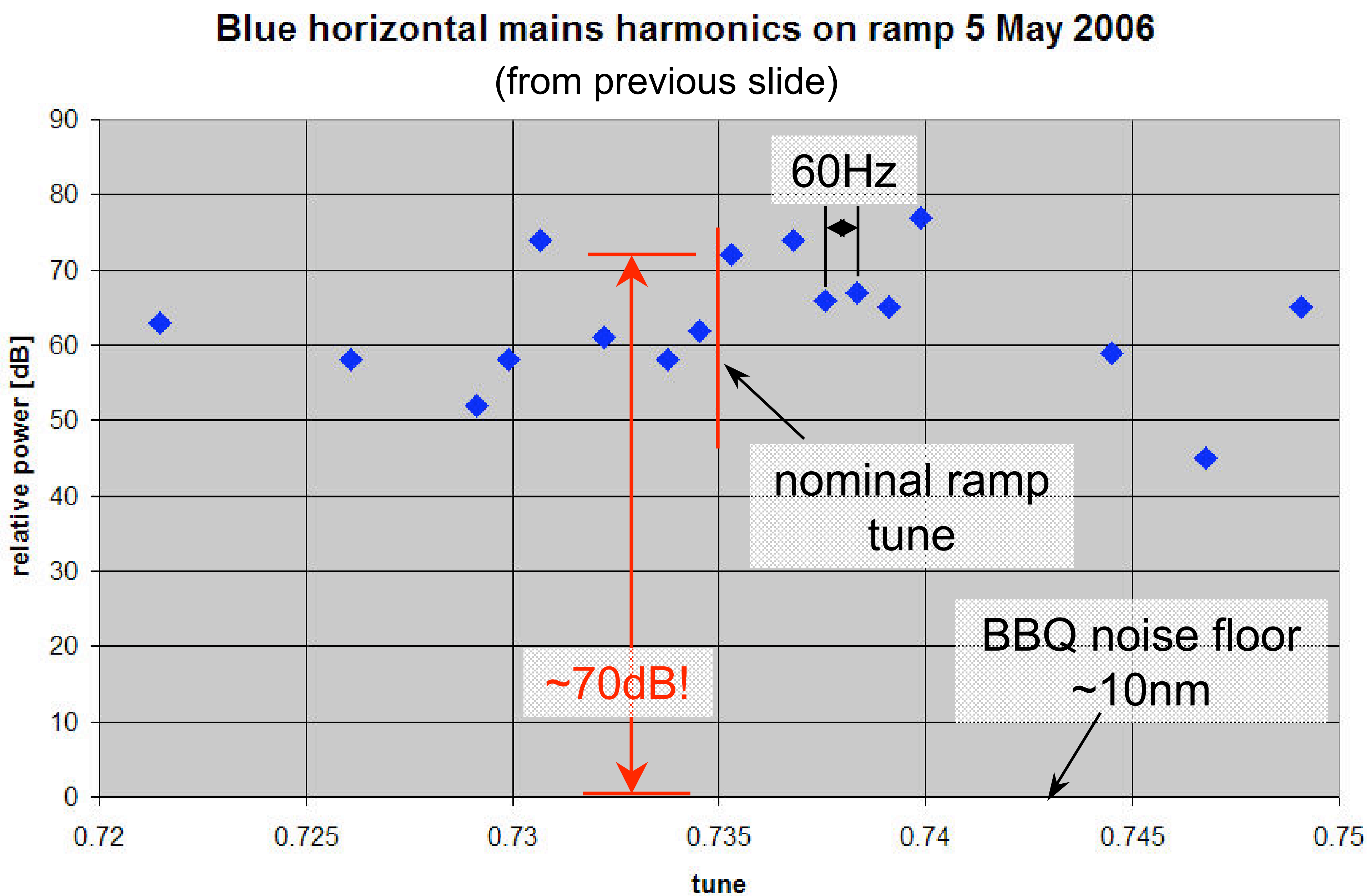
LARP

3D-BBQ system still suffers from phase noise problems
- very sensitive detector
- sudden phase losses
- 60 Hz lines still troublesome

Mains Harmonics
- Excitation of betatron line by power supply ripple
- Seen at CERN, FNAL, BNL,…
- Understood for over a year
- Not a RHIC priority in higher scheme of things
- Main obstacle to further feedbacks development

Will continue studying system performance throughout the RHIC run and finalize system design by the end of the summer


TRACE A: Ch1 Spectrum
A Marker 336.2 ks 17 274.599 2 Hz -47.126 dBm
-20 dBm
-120 dBm
Mains Harmonics during RHIC ramping with no kicker excitation
720Hz
betatron 'line'
Center: 20.704775 kHz
Span: 9.765625 kHz



Blue horizontal mains harmonics on ramp 5 May 2006
(from previous slide)
relative power [dB]
90
80
70
60
50
40
30
20
10
0
0.72
0.725
0.73
0.735
0.74
0.745
0.75
tune
60Hz
nominal ramp tune
~70dB!
BBQ noise floor ~10nm

Mains Harmonics - 12 phase balancing

BBQ noise floor ~10nm

Mains harmonics ~70dB above this

- ~30μ excitation due to mains harmonics
- LHC spec is <1μ excitation permitted

Tune tracking requires excessive kicker power

- emittance blowup
- cannot do development work
- need 12 phase balancing

April 05 Tune Feedback Design Review

- **"12 phase balancing is highest priority"**

CERN's TF requirements

CERN
CH-1211 Geneva 23
Switzerland

the
Large
Hadron
Collider
project

LHC Project Document No.
LHC-B-ES-0004 rev 2.0
CERN Div./Group or Supplier/Contractor Document No.
SL-BI
EDMS Document No.
328136

Date: 2004-02-13

Functional Specification

ON THE MEASUREMENT OF THE TUNES, COUPLING & DETUNINGS WITH MOMENTUM AND AMPLITUDE IN LHC

Scope, Boundaries, Responsibilities...

LARP

CERN provides all hardware for LHC

- kicker amplifiers, kickers, and pickups
- Direct Diode Detection AFEs
- Digitizer boards
- DAB64 Boards - FPGA for processing plus VME interface
  - LHC (BPM, BLM, BCM,...) and LARP (PLL, Lumi, Schottky) standard
- VME crates and crate computers for CERN installation

LARP provides all software up to LHC Control System

- VME crates and crate computers for LHC test installation at BNL
- gate array programming
- FEC programming
- LabVIEW control program, collaboration on LHC equivalent (FESA)
- specification and testing of LHC TF Applications software
- testing at RHIC, with and without beam
- pre-beam and beam commissioning support at LHC

Tune Feedback Planning

FY06

Demonstrate functioning system on RHIC run

Develop electronics and firmware to support RHIC and SPS runs

Complete system development in RHIC

Deliver and test a system for CERN SPS run

Final Design review

FY07

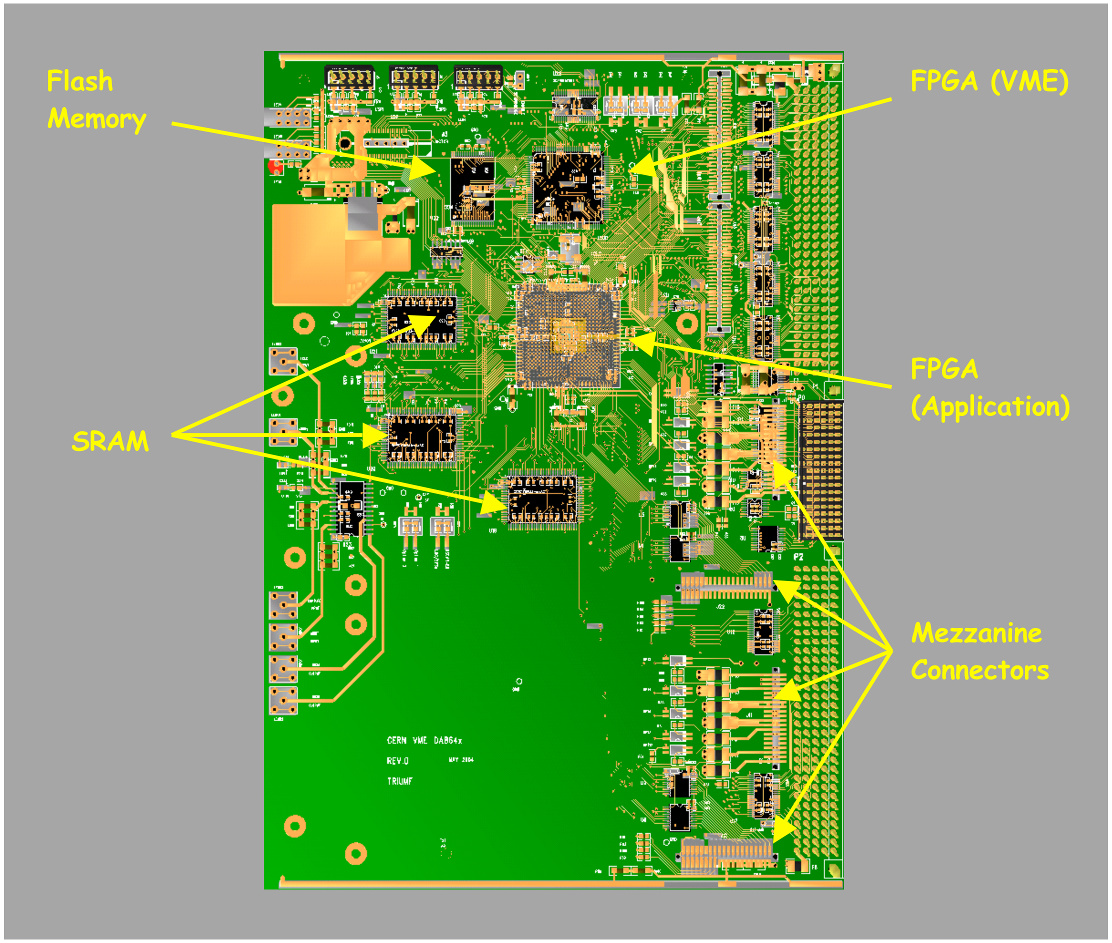
All 4 planes ready for LHC commissioning

All firmware and software ready for beam commissioning

Support installation and hardware commissioning

Support beam commissioning

LHC DAQ Interface - DABIV Board



J. Gonzales, CERN

LARP DAQ Workshop

- Attended by representatives of all labs
  - April 25, 2006
- Daryl Bisop (TRUIMF), designer ot the DAB board, gave a comprehensive descrption of the board design and its firmware programming
- Rhodri Jones did a live demonstration of the hardware functionality at LBL
  - Used signal from pulse generator, processed by LUMI analog shaper
- Round table discussion on how to implement system at LARP labs

DAQ software/firmware for LARP instruments

- Real Time OS problem to compile LynxOS at US labs
  - This stalled our efforts for months
  - Licensing problem
- LabView proposed by CERN
  - Use VME-USB bridge card
- LARP labs can develop expert Vis in LabView and deliver to CERN
  - Uses the bridge card in the US
- CERN implements the FESA interface, provides LabView connection
- Expert panels available through CERN’s FESA
- LARP labs provide functional specification of memory interface
- CERN develops GUIs for device controls
  - Both expert and operator

Open Issue/Opportunity

LHC@FNAL opens the door to experiments or observations at LHC directly from LARP sites

- FNAL is leading the way

Ideal for ‘passive’ devices

- I.e. Schottky monitor, luminosity monitor
- Could make present effort on Shottky more effective

Not clear how much will be available by commissioning

- CERN controls must be deeply involved for this to happen
- Priorities may not be aligned

CERN is now looking at ways to facilitate

Common Instrumentation Plans

Commissioning teams created at CERN, LARP plans to provide instrumentation commissioning support

New task proposals have been presented in a common session

- AC dipole
- Synchrotron light based diagnostics

Instrumentation group will do its assessment with CERN input

LARP Instrumentation Integration Plan

Planned documentation for each instrument

1. FS - Roles and Responsibilities
   Defines who does what, when
2. ES- Technical Specification
   Complete description of the device, its interfaces, its requirements….
3. ES - Functional Spec (of DAB 64x interface)
   Definition of what functions and features are included in the data acquisition system
4. ES - Memory Map of Firmware
   How the data is transferred to the control system
5. Any other document
   (ES) Safety, installation, HW checkout and commissioning,
6. FS - Acceptance Plan and signoff list
   Contains a list of deliverables from LARP to CERN
   Signoff list
   Once accepted, defines the end point of LARP's contribution to the instrument

FS= Functional Specificationl ES=Engineering Specification

Implementation

The above docs have approvals on both sides

- CERN and LARP

PIs are the single points of contact at each side of the ocean

Documents reside in EDMS and in LARP's databases

We aim to have the first two and the last one ready for the DoE review in June

New Tasks

LARP

Several new tasks are emerging

- AC Dipole
- Synchrotron light based diagnostics

Being considered with other AS new proposals

As the existing tasks come to an end, funds will become available for new proposals

Instruments are chosen in close collaboration with CERN

- Current devices were not part of baseline design of LHC

Conclusions - Challenges

- Funding
  - We are working with LARP management to continue securing adequate funding
  - With LHC commissioning approaching, we cannot tolerate schedule slips

- LARP task sheets continue to define scope and budget year by year
- Funding requests are also managed through task sheets
  - Detail ‘project’ reviews validate overall cost and schedule

- Integration with beam commissioning activities is essential to the survival of the instruments provided by the LARP collaboration and LARP is planning accordingly

Summary

- LARP Instrumentation will build, commission, and integrate into LHC operations advanced instrumentation and diagnostics for helping LHC
  - reach design energy
  - reach design luminosity

- Strong collaborative efforts are in place and evolving
  - Tune feedback is fully leveraging RHIC experience and includes CERN staff
  - Lumi plans to do the same with RHIC run 6
  - Schottky's experience at FNAL is a great asset
    - synergies with BNL are fully leveraged
  - US colliders are an essential test bed for system development

- This program will advance the US HEP program by
  - Enhancing US accelerator skills
  - Developing advanced diagnostic techniques that will apply to present and future US programs
  - Help maximize LHC performance

LARP